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FLEMING, J.A.

The centenary of the electric current.

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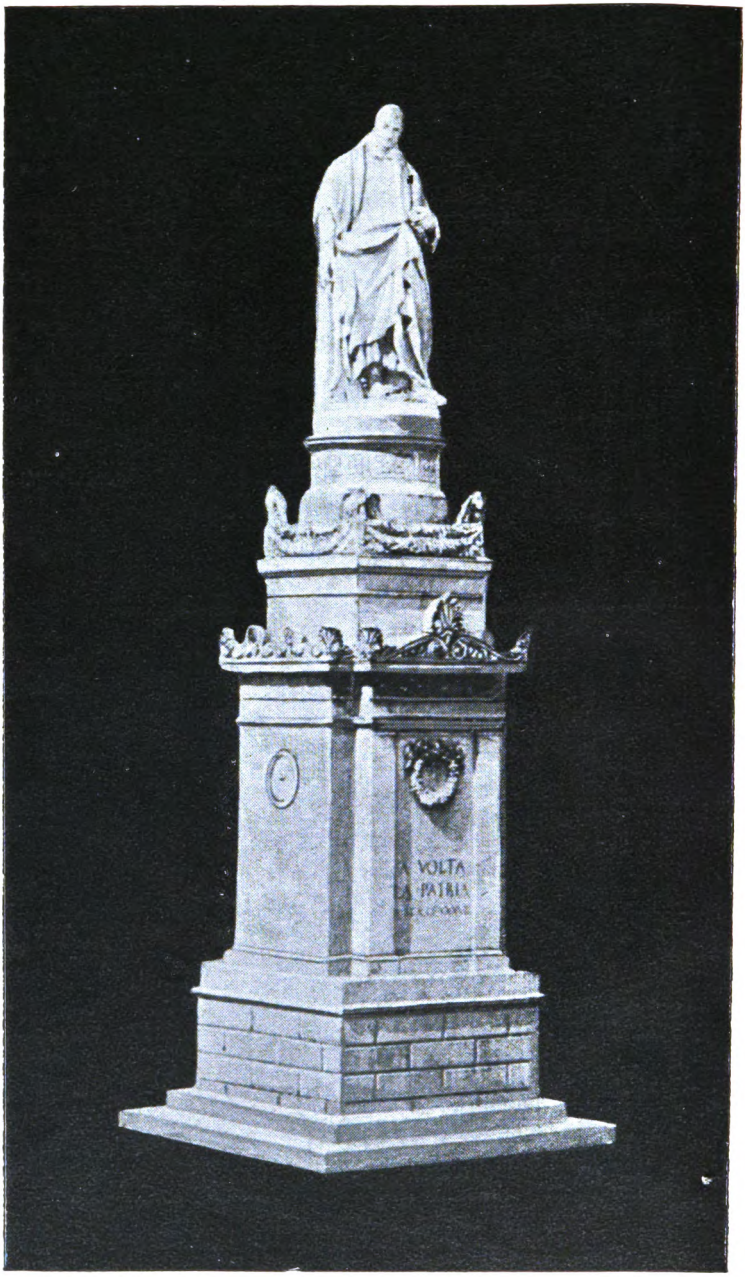

THE STATUE OF ALESSANDRO VOLTA IN THE MARKET PLACE OF COMO.

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[Frontispiece.

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THE CENTENARY

OF THE

ELECTRIC CURRENT.

1799-1899.

A Lecture

DELIVERED IN THE CONNAUGHT HALL, DOVER, ON MONDAY EVENING, SEPTEMBER 18th, 1899, DURING THE MEETING OF THE

BRITISH ASSOCIATION

FOR THE

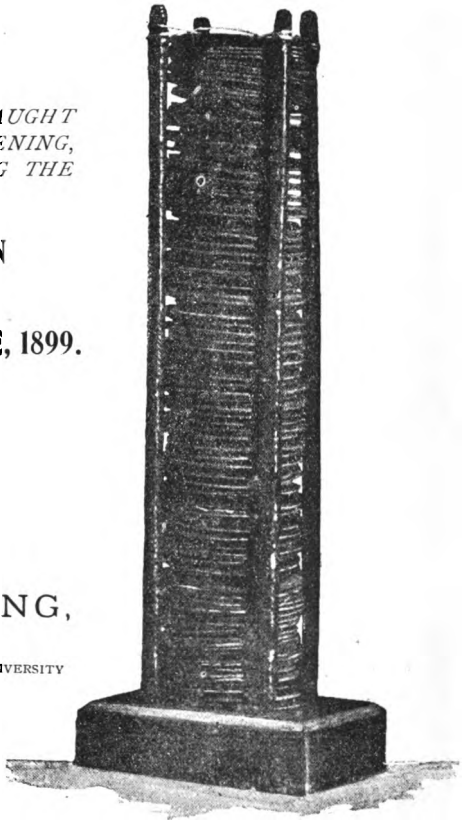
ADVANCEMENT OF SCIENCE, 1899.

BY

Dr. J. A. FLEMING,

M.A., F.R.S., &C.,

PROFESSOR OF ELECTRICAL ENGINEERING IN UNIVERSITY COLLEGE, LONDON.



ORIGINAL VOLTA PILE.

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PREFACE.

THE invitation to undertake the duty of delivering an Evening Discourse to the Members and Associates of the British Association, meeting at Dover on the day (September 18th, 1899) when a Congress of Electricians assembled at Como to commemorate the scientific work of Volta, naturally suggested for consideration the subject most closely connected with his illustrious name.

Italy has been the native land of many philosophers whose names stand inscribed high up on the scrolls of fame, but the investigator who first gave the world, a century ago, the means of creating the Electric Current, is secure in his unrivalled claim to remembrance by posterity by the results which have followed from his successful work.

J. A. F.

September, 1899.

The illustration on the title page, and Figs. 1, 2 and 3 in the text, are reproduced from blocks kindly lent by the publishers of a pamphlet edited by Prof. P. Blaserna, describing the Volta exhibits collected for the Como Exhibition, 1899. For permission to reproduce these photographs of original apparatus the author desires to record his acknowledgements and thanks.

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THE

CENTENARY OF THE ELECTRIC CURRENT.

1799—1899.

In the market place of Como, overlooking one of the fairest of the Italian lakes, a statue stands, erected to commemorate an illustrious experimentalist and an invention epoch-making in the history of the world. The statue represents Alessandro Volta (see *Frontispiece*), and the invention was the instrument which gave us the first practical means of generating a continuous electric current. Volta was led up to the achievement that secured for him an imperishable fame by a long course of experimental research, which bore fruit of a splendid and enduring kind.

Hence the centenary of his ever-memorable investigations, which opened a new chapter in the history of electrical discovery by giving to the world the Voltaic pile, is being fitly celebrated by men from many lands meeting at this moment in his native town.

Alessandro Volta was born at Como, in North Italy, on February 18th, 1745. When 29 years of age he received a public appointment as teacher of physics, in the gymnasium of his native town, and three years afterwards relinquished it to make a tour through Switzerland. In 1779 he was elected to occupy the Chair of Physics in the University of Pavia. Previously to this event he had attracted attention to himself by devising, in 1775, the electrical instrument called the *Electrophorus*. This invention grew out of a study he had made of the subject of electrostatic capacity. These inquiries led him to the construction of the electrical condenser and its use with an electroscope, and thus paved the way for his subsequent important work on contact electricity by placing him in possession of a most delicate means for detecting electrification.

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Volta also devised the first form of absolute electrometer, an instrument by which electric potential difference is determined by balancing forces due to electrification against the force on standard masses of matter due to gravitation. This electric balance was afterwards used by Sir W. Snow Harris in his researches, and was given its present perfect form by Lord Kelvin.

Volta employed these electroscopes, and other special forms devised by himself, in the study of atmospheric electricity.

About the year 1790 Galvani's historical observations on the muscular contractions produced in a recently killed frog started into existence the train of investigations which led Volta ultimately to the invention of his pile. An interpretation of Galvani's experiments in the light of modern knowledge seems to show that the first observed fact was that contractions could be produced in the muscular system of a frog by electric waves, set up by an electric spark produced at a distance. The endeavour to ascertain if atmospheric electricity could produce the same result led probably to the other recorded observations, in which the same contractions were obtained when the frog was suspended by a copper hook from an iron railing. Volta followed up these initial observations with philosophical insight of the highest kind, and by cautious deduction and reference at every stage to experiment, finally gained possession of the important facts of contact electricity, demonstrated the existence of electromotive force due to the contact of metallic and electrolytic conductors, and compelled the acceptance of his views by the world.

Volta lived to see the great development of the subject at the hands of his illustrious contemporaries, and, in particular, the remarkable electro-chemical discoveries of Davy. During the last quarter of a century of his life, he himself, however, added but little to research, and he died in retirement at Como, on March 5th, 1827.

His chief invention, the Electric Pile, was made about the end of 1799, and accordingly, in the present year (1899), it was arranged to celebrate the centenary of this important event at Como by a congress of electricians, and by an exhibition of historic apparatus constructed by Volta. A calamitous fire, however, which occurred on July 8th, 1899, destroyed the building in which these invaluable relics had been collected. Many of these precious heirlooms of science perished in the flames, and much of the handiwork of the master was reduced to ashes. Fortunately, however, the destruction of Volta's apparatus, collected together from numerous museums, did not prove to be so complete as at first supposed and many original specimens were rescued in time from annihilation.

It is a familiar fact that almost exactly one hundred years ago Volta communicated to Sir Joseph Banks, then President of the Royal Society of London, a letter dated March 20th, 1800, in which he describes his invention of the electric current-generating appliance, since known as the voltaic battery or pile. This Paper, printed in the *Transactions* of the Royal Society, as having been read on June 26th of the same year (*Trans.* Roy. Soc., Vol. XC.,

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Part I., p. 405), stands as a landmark in the intellectual record of our race.

No thoughtful person can regard the modern uses of the electric current thus given to us by Volta, or review the astounding results which a century of its possession by the world has brought about, without feeling some desire to know what is known of the inner mechanism of this nimble servant of mankind.

According to Garcke ("Manual of Electrical Undertakings," 1898-99) the total amount of capital invested in Great Britain alone in electrical undertakings in 1899 is as follows :—

Telegraph Companies (not including Postal Telegraphs)	£31,983,365
Telephones (not including Postal Telephones)	7,159,368
Electric Supply Companies...	8,407,628
Municipal Electric Supply	5,734,938
Electric Traction	14,406,140
Electric Manufacturing Companies	10,535,937
Miscellaneous Electrical Enterprises	6,514,644
Total	£84,742,000

Having regard to the immense development of electric traction in the United States, and to the enormous extent of electric lighting in Europe, it is clear that the capital invested in electrical commercial undertakings in the world at present (1899) is to be reckoned in hundreds of millions sterling. This is chiefly the result of electrical engineering in the last twenty years, based on scientific discoveries made during the present century.

My aim to-night will be, by a few experimental demonstrations, to direct your thoughts to consider the chief conclusions reached after a century of investigation on this matter, and to indicate the problems which yet remain to be solved before we can answer with any considerable degree of approximation the question so often asked, What is an electric current? In so doing I must not assume that the language of technical electricity is familiar to all present, and I shall, therefore, cast myself on the indulgence of professed electricians if for the sake of others it is necessary to deal at first with some elementary matters.

Leaving out of account unnecessary historical statements, we may say that Volta made two important discoveries, or, rather, made a practical contrivance and

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elucidated its operation by a scientific discovery. The discovery was the fact that if pieces of different metals—say zinc and copper—are placed in contact and then separated they are found to be in different electrical states. The manner in which this effect can best be shown is to employ two perfectly flat discs of zinc and copper, each provided with an insulating handle. The discs have their faces very slightly varnished with an insulating varnish. One of these discs, say the lower one, is connected to an electroscope having aluminium leaves, and the other is held in the hand. If the discs are superimposed and connected for a moment by a copper wire, on lifting off the upper disc the leaves of the electroscope diverge. The copper disc under these circumstances is very slightly negatively electrified and the zinc disc positively.

If there are any to whom these terms convey no meaning let me explain that the process we call electrification is one which can take place in two modes, called, for the sake of distinction, positive and negative. These terms are purely conventional, and are merely used because we know that these two modes of electrification are antagonistic and destroy each other if present in the same place at the same time. Moreover, one kind cannot be produced without an equal quantity of the other.

The act of producing an electrical charge is regarded, not as one of *creation*, but of *transfer* or *displacement*, by which an increase of something at one place is accompanied by a decrease of the same thing at another. Volta originated the useful term *electromotive force*—which has survived to this day—to describe the active cause producing this electrical separation or transfer at the place where the metals touch.

Volta was led by his investigations to classify all substances into two groups, which he called respectively conductors of the *first* and *second* class. The first class comprises metals and charcoal or carbon; the second all fluid conductors, such as solutions of acids, salts, &c.

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Volta distinguished conductors of the second class, by a somewhat unscientific classification, into aqueous, spirituous, mucous, gelatinous, saponaceous, saccharine, saline, acid, alkaline and sulphurous.

With regard to the conductors of the first class, now called the metallic conductors, Volta discovered the important fact that if any number of pieces of different metals are in contact and form a series, the electrical potential difference between the end or terminal pieces of the series is just the same as if they were directly in contact and the others absent. Hence it follows that if an equal number of plates of zinc and copper are piled one on the other alternately, the two terminal pieces of zinc and copper exhibit only the same feeble electrical potential difference or state that they would do if directly in contact, and there is no summation of the effects of the separate pairs. It also follows that, in a circuit composed of several metals, the sum of all the contact electromotive forces is zero, and there is no resultant electromotive force.

Previously, however, to this discovery of the contact electrification of metals, Volta had been guided by his own particular theoretical views to try the effect of inserting a conductor of the second class, now called an electrolyte, between pairs of conductors of the first class, and by this brilliant suggestion he gave the world his electric pile. Placing over one another numerous discs of zinc, cloth wetted with salt water and copper, in the same repeated order, he found that the composite column or pile exhibited far more marked electrical properties than is the case with a single zinc-copper couple, and it enabled him to accumulate the electrical effects, or the electromotive forces due to each pair of metallic contacts taken alone (*see* Figs. 1 and 2). In other words, he was able to multiply to any required extent contact electromotive force. Thus a pile, say, of twenty pairs of zinc and copper discs with wet cloth between each pair, possesses just twenty times the electromotive force of one pair.

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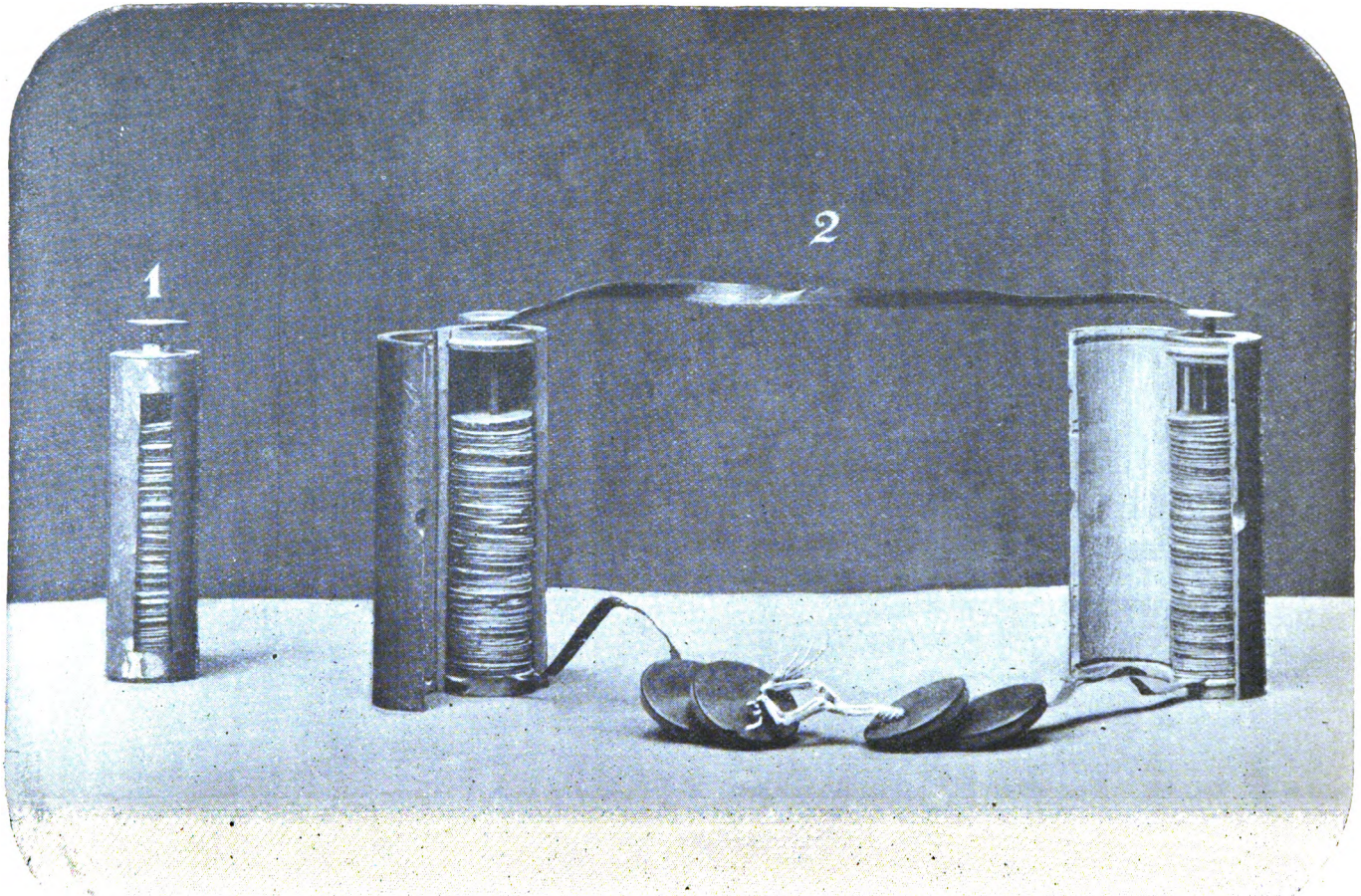

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Time will not permit me to enter into even the briefest possible discussion of the famous controversy which then arose as to the source of the electromotive force of the voltaic element or pile.

A study of Volta's Paper, published in the *Transactions* of the Royal Society of London for 1800 (Part I.), entitled "On the Electricity Excited by the Mere Contact of Conducting Substances of Different Kinds," suggests that it is not improbable Volta was led to the construction of his famous pile by considering the structure of the electric organ of the torpedo or electric ray, which is one of the best-known forms of several types of animal organisms furnished with an electric generating apparatus. Walsh, in 1778, had made numerous researches on the electric powers of the torpedo, and Volta was, without doubt, acquainted with the general nature of the characteristic tubular or laminated organ in which this electric power resides. He himself compares his pile with this natural current-producing electrical organ and finds a similarity of structure. In another place, speaking of the accumulative property of the series of wet and dry conductors he says: "Each couple, accordingly so arranged, adds a degree of force, so to speak, to the electric current." His other researches on the contact electricity of dry metals led him to regard the function of the liquid on the pile as merely conductive, but he evidently considered that the moist conductor, by separating alternate dissimilar metallic pairs of plates, permitted an addition of the contact forces of each pair to be made.

A very complete discussion of the modern state of the controversy as to the seat of the electromotive forces in a Voltaic cell was given by Dr. O. J. Lodge in 1884 (*see* British Association Report, 1884, pp. 464–599). Also in a Paper read before the Institution of Electrical Engineers in 1885 (see *Proc.* Inst. E.E., Vol. XIV., p. 186, 1885; also *Phil. Mag.*, March 1885). A contribution was made to the subject by the author in 1874 (see *Phil. Mag.*, June, 1874, "On the Contact Theory of the Galvanic Cell"). One of the most recent and valuable summaries and statement of facts connected with Volta's contact electrification was given in a Royal Institution Friday Evening Discourse by Lord Kelvin, "On Contact Electricity in Metals," May, 1897 (see *Proc.* R. I., Vol. XV., p. 529).

Volta's researches on contact electrification started one of the historical controversies of science, and it is not too much to say that probably, even now, no two physicists would state their creed as to the origin of the electromotive force in the voltaic cell in precisely the same terms. We must, however, dismiss from view this contest of opinion merely by saying that whilst Volta himself considered the place of contact of the dissimilar metals on conductors of the first class to be the true seat of the electromotive force, others, following Fabroni in a Paper

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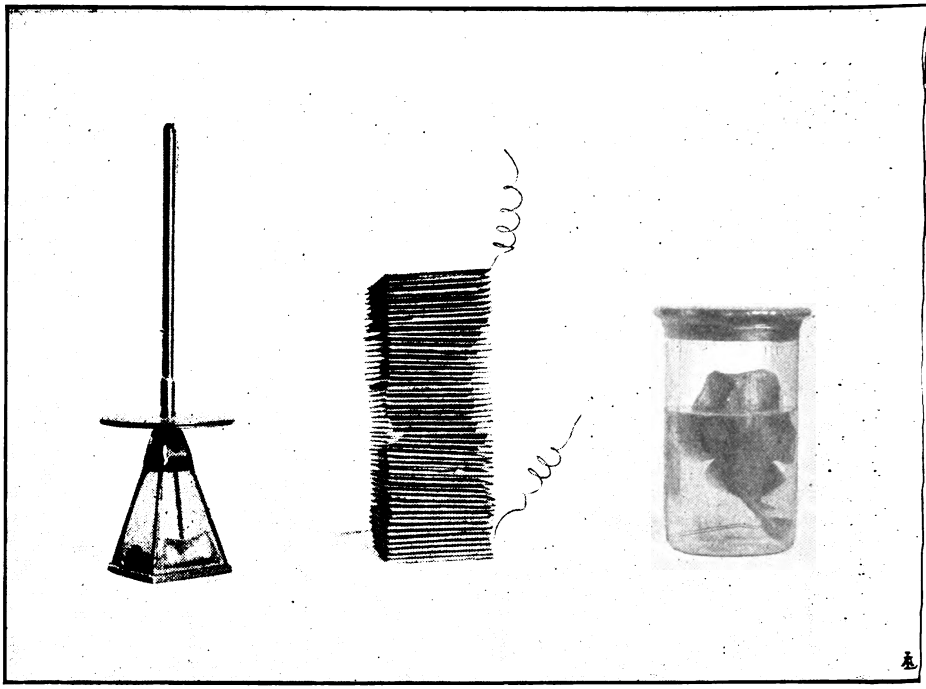

FIG. 2.—Condenser, Pile and Torpedo.

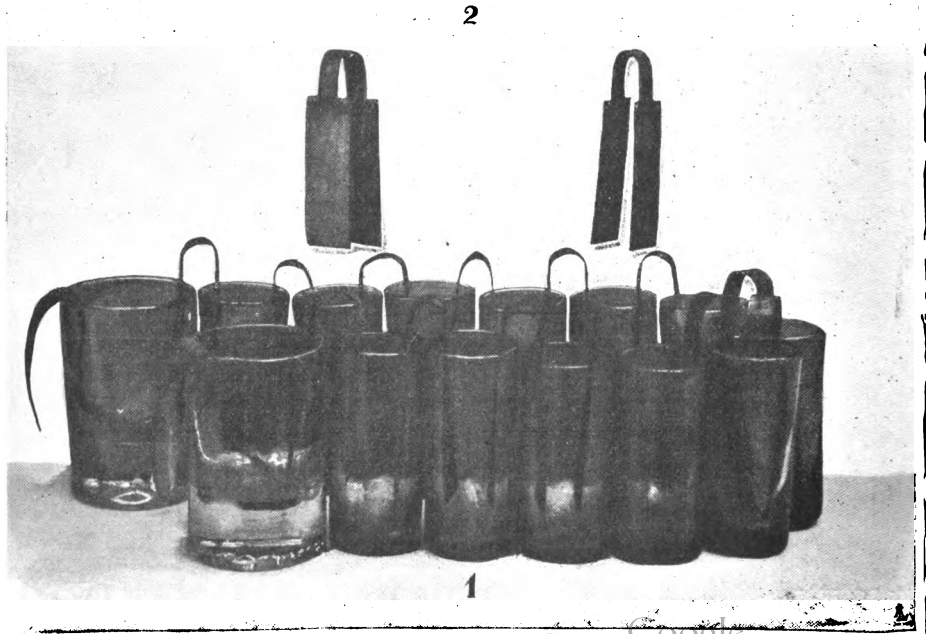

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FIG. 3.—Original Volta "Couronne de Tasses."

published in Florence in 1799, have regarded the effect as due to the chemical action of the conductor of the second class on one or both of the metals forming the rest of the circuit. In the case of clean dry metals in contact the electromotive force is by some ascribed to the oxidizing action of the air.* Wollaston in 1801 showed clearly that the operation of the pile was always accompanied by chemical changes in it.

Let us, at this stage, now examine the results which take place when a simple voltaic cell or combination is formed. In a glass vessel we place some water slightly moistened with sulphuric acid, and in this we place a rod of zinc and one of silver. If the zinc and silver do not touch no visible action takes place. Pure zinc is perfectly insoluble in dilute sulphuric acid. If, however, the zinc and silver are made to touch by joining across them a silver rod or wire, a violent effervescence is then seen to take place around the silver rod. This effervescence is due to escaping bubbles of hydrogen, and indicates a chemical action. You will notice that we have here three substances in contact—zinc, silver, and acidulated water forming a circuit. During the contact of the three substances we have an electromotive force acting in the circuit. We have also a chemical action taking place between the materials in the vessel by which the zinc is gradually dissolved away by the dilute acid, and in its place we have produced sulphate of zinc, a compound possessing less chemical energy than the zinc and sulphuric acid taken together which formed it. Finally we have an exhibition of new and peculiar properties in the connecting wire and the circuit which are described by saying that an electric current is flowing round the circuit.

A series of these cells may be arranged, as was done by Volta and Cruickshank, into a battery (*see* Fig. 3), and the end

* The most recent researches on contact electrification (*see* Mr. J. Brown, *Proc.* Roy. Soc., 1899, p. 369) do not, however, lend support to the view that the surrounding gas in which the metals are immersed is an efficient cause of the contact potential difference.

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plates may be joined by a circuit-closing wire, which then becomes the seat of an electric current. The peculiar property of this voltaic arrangement of conductors of the first and second class is that it can maintain in and around the circuit-closing wire this physical state called an electric current.

Our business this evening is chiefly to investigate, as far as possible, the nature of this effect. Let me, at the outset, warn those not much versed in electrical phraseology against being misled by electrical terms. One of the matters upon which I shall have to lay most stress, is that the action or operation we call an electric current is as much or more *outside* the wire or circuit than in it, and there is no foundation for the view suggested by the term *current* that we are concerned with an operation resembling the flow of water in a pipe. Electrical terminology is in a transition state, and many words in use are saturated with old and erroneous hypotheses, though still employed from force of habit or dislike of change. The term *electric current* is to be understood as merely a convenient expression denoting the sum total of all the peculiar physical phenomena present in and around the circuit of conductors. We shall, for convenience, denote the wire which connects the end plates of the pile or series of cells as the *circuit-closing wire.*

I wish, in the next place, to direct your attention carefully to the effects which the pile or battery produces in the surrounding medium or space, both when the circuit is open and when it is closed. Suppose the circuit in the first place open and the end plates of the pile connected to two plates of metal placed in proximity, one of which is fixed and the other movable, it is found that there is a *stress* or *pull* between them which draws them together. On the screen we project the shadow of such a pair of fixed and movable plates, called an electrostatic voltmeter, and connecting a battery to the plates we find them drawn together with a certain force. This attractive force

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between plates attached to the terminals of a Volta pile is of exactly the same character as that which exists between two light objects connected to the terminals of an electrical machine, one being charged with positive electrification and the other with negative.

It follows from facts first discovered by the celebrated Henry Cavendish that, with a given battery, the attraction not only depends on the form and distance of the plates, but upon the material or dielectric, as it is called, in which they are immersed. If the plates connected to the pile are placed, say, in turpentine or alcohol, the plates under the same conditions will attract each other more strongly than they would if they were simply in the air.

Faraday was anticipated in his great discovery of the true function of the dielectric by Henry Cavendish. Cavendish's work, carried out between 1773 and 1781, A.D., remained, however, unknown until his unprinted Papers were re-edited and published a century afterwards, in 1879, by Prof. Clerk Maxwell, from the original manuscripts belonging to the Duke of Devonshire. Cavendish not only discovered that the nature of the dielectric or non-conductor affected the electrical capacity of a condenser or Leyden pane formed with it, but he made fairly accurate measurements of some dielectric constants (*see* "The Electrical Researches of the Hon. Henry Cavendish," Introduction, p. liii., by Prof. J. Clerk Maxwell).

Faraday devotes to the consideration of the nature of electric charge the Eleventh Series of his "Experimental Researches in Electricity" (Vol. I., p. 360), and in this is announced (in 1835) his discovery of specific inductive capacity. It then follows, from very elementary principles that since the presence of the dielectric increases the quantity of electrification conveyed to a given condenser of proper form by a given potential difference or electromotive force in the ratio of K to unity (where K is the dielectric constant), that the electric force between two bodies charged to a constant potential difference is increased in the ratio of K to unity when the dielectric round them is changed from air to another having a constant K. Also it follows that if the quantity of electrification of the charged bodies is kept constant the stress between them varies inversely as the dielectric constant of the dielectric in which they are immersed, all other circumstances remaining the same (*see* Maxwell's "Treatise on Electricity and Magnetism," Vol. I., § 94, p. 113).

Moreover, this attraction is a proof that there is energy in some form stored up in connection with the system. It is an important matter to ascertain exactly where the energy resides. You will notice that we have in this case two conducting plates separated by what is called a non-conductor, insulator or dielectric.

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We can, following Cavendish and Faraday, prove quite easily that the energy is stored up in the dielectric, and not in the metal plates. This may be shown as follows:—

Let us take two glass soda water tumblers, having outer and inner jackets of tin, and connect the inner and outer jackets of one of them for an instant with a battery, or, which comes to the same thing, with an electrical machine. The arrangements form two Leyden jars. The question then is, Does the energy of the charged jar reside in the metal jackets or the glass? If the energy resides in the metal plates of this condenser, as it is called, the removal of these plates and the substitution of the two other plates belonging to the uncharged jar will carry away the energy with them. If, however, the energy resides in the glass or dielectric the substitution of the new metal jackets will still leave the energy where it was. The simplest proof that energy *is* still associated with the apparatus when so treated, and the jackets exchanged, is to connect the two metal plates with a wire. You see a flash or electric spark at the contact places, and if that connection were made through the human body you would not be left in any doubt as to the fact that energy, even in dangerous quantities, may be stored up in the dielectric. When the experiment is performed, as was first done by Franklin, we find that changing the metal plates of the condenser still leaves the major portion of the energy in the condenser, and the inference is that the energy is chiefly stored up in connection with the glass jar or plate.

Franklin showed (Collected Works, Vol. V., p. 201) that if a Leyden jar or condenser is made with removable coatings, and also provided with a pair of extra coatings, the electric charge of the jar or condenser, when it has been charged, is not removed by changing the original metallic plates for new and uncharged coatings; in other words, that the charge resides chiefly in the glass or other dielectric, and not in the coatings. Cavendish, however, tried the same experiment with an air condenser, and found that changing the air between charged condenser plates did not destroy the electric charge of the condenser. A consideration of these facts indicates that some considerable part of the charge of a condenser constructed with a solid or liquid dielectric is removed if the dielectric is changed or taken away; but that some part of the charge, and in the case of a gaseous dielectric nearly the whole of it, is

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independent of the material dielectric between the plates. Hence it follows that empty space, or a perfect vacuum, must possess the property of taking up energy in the form of an electric charge.

A little careful reflection on the facts exhibited will reveal that the operation of the battery on the insulating plate is to produce a change equivalent to a strain which releases itself when the two metal plates bounding its surface are subsequently connected by a conductor. In electrical language this strain is called a *displacement*, and is said to be produced by electromotive force. The displacement takes place along certain strain lines, and it represents a storage of energy in connection with every cubic inch of the dielectric, just as much as there is a storage of chemical energy in connection with every pound of guncotton. Hence, in association with Volta's pile, there is an association of energy, called *electrostatic energy*, distributed through, and contained in, the surrounding medium or dielectric. The end plates of the pile, or any plates connected to them, tend to pull each other together in virtue of this stored electric energy, just as a gravitational attraction of two masses or of the earth and a stone manifests itself in consequence of the energy storage caused by the presence in any place of two gravitating masses. This attraction is greatly modified by the material between the plates, but it exists even if the plates are placed in a perfect vacuum. Thus static or potential energy is stored up in the medium between the plates, and can so be stored even if the medium is a perfect vacuum.

In the next place, if the circuit of the pile is closed by a wire, we find in addition an effect taking place in the space round the wire of a different kind. We are able to show that the space is possessed of magnetic qualities and is said to be traversed by *magnetic flux*.

If we place the circuit-closing wire perpendicular to a plate on which are fixed a number of little compass needles, we discover that these needles, as long as the battery circuit is not closed, are unaffected by the wire and place themselves in the direction of the magnetic

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meridian or magnetic north and south directions. When, however, the pile is connected to the wire, the compass needles instantly arrange themselves, as far as possible, in directions along circular lines described round the wire as a centre. The magnetic needles merely indicate the direction of that which is called the magnetic flux at any point just as weathercocks indicate the direction of the wind. Hence the experiment shows us that round the wire there is a distribution of magnetic flux in circular lines. This magnetic flux can be directed one way or the other according to the mode of connection of the wire with the pile, and if the connection is changed, the little compass needles turn right-about-face, and change their direction also.

When the flux is steadily in one direction we say that the current is *continuous*. When the flux is first in one direction and then in the reverse, we say that the current is *alternating*.

We shall, in some of our experiments this evening, use an alternating current which alternates 200 times a second; in others an alternating current alternating one or two million times a second; and finally one which alternates several hundred million times a second. Instead of employing compass needles, we may sprinkle steel filings on a glass plate having a hole in it through which the circuit-closing wire is led (*see* Fig. 4), and we then find that each little fragment of steel sets itself in the direction of the flux and the whole series delincate the circular lines of flux. The steel filings therefore serve to render visible the direction of this magnetic flux, just as the dust in the air of a room serves to render visible the direction of a beam of light.

In the light of these experiments, we see that the circuit-closing wire of a Volta pile must be thought of as surrounded with rings of magnetic flux, and this flux manifests itself when continuous by imposing a certain direction upon magnetic needles. Each magnetic needle

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has two poles—a north pole and a south pole, and we cannot separate the two; but by a device due to Faraday we can investigate the action of the flux on each pole separately.

By placing two magnets vertically and fixing them to a central boss pivoted like a compass needle on the end of a vertical wire we can send a current up between the two like lower poles and take it off by means of a contact pin attached to the central boss. This pin moves freely in a concentric circular trough of mercury which is connected to the opposite end of the battery. When this is done, we find

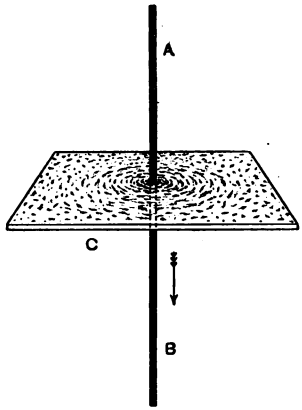

FIG. 4.—Circular Lines of Magnetic Flux round the Circuit Closing Wire A B of a Volta Pile Delineated by Steel Filings.

that the lower magnetic poles begin to revolve rapidly round the central vertical wire, moving one way or the other according to the nature of the pole and the mode of connection of the vertical wire with the pile.

These experiments indicate that round the circuit-closing wire of the pile there is something of the nature of a vortex or whirlpool which carries magnetic poles along with it, just as a water whirlpool carries boats or floating objects round with it. This magnetic whirlpool is appropriately called the magnetic flux. The magnetic flux

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always takes place along closed lines, and it is clear we may speak of it as having a direction as well as a path.

Certain physical quantities can only exist at all if they exist simultaneously all along certain self-closed lines. These quantities are called *circuital quantities*. Of this nature are the movements of an incompressible fluid in an enclosed space, and the effect above called a magnetic flux. Electric displacement may or may not be circuital, but magnetic flux is always circuital. Hence there is no such thing as an end or termination to a line of magnetic flux. Electric current is likewise a circuital quantity, and its analogy in this respect to a flow of incompressible fluid was the chief reason for the adoption and retention of an electrical term so suggestive of a movement of liquid.

By a usual convention we define the direction of a magnetic flux line as the direction along which a north magnetic pole would move if free to travel. If the circuit-closing wire has the form of a spiral it is easy to see that the magnetic flux round one part of the wire embraces also other parts of the wire, and hence intensifies the action in the space outside the wire. If a spiral circuit has, say, ten turns, then a little thought will convince you that the flux is linked much more than once with the whole circuit. In fact, if the turns of the wire are brought close together, the total linking of flux and circuit is nearly 100 times greater than it would be if the wire were straightened out and yet remained connected with the same battery.

In order to create this magnetic flux we have to expend physical energy, or do work; and the flux when made represents a storage of energy of a peculiar kind. Deferring for a moment experiments to prove this fact, the point I wish now to press on your attention is that, in association with Volta's pile, when the circuit is closed, we have *two forms of energy*. We have it in one form called electric energy, in virtue of the electric strain which exists in the surrounding medium between the ends of the pile and all the parts of the connecting wire. Also, we have it in another form as magnetic energy, in virtue of the magnetic flux which exists in lines embracing the circuit-closing wire. These two types of energy, as we shall see later, can be converted into one another.

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At this stage it will be useful to point out that every piece of magnetised steel has a distribution of magnetic flux associated with it permanently, just as the wire closing the circuit of a Volta pile has an evanescent or temporary magnetic flux linked with it whilst it remains in connection with the pole. The distribution of flux round a bar magnet is now shown to you. Likewise the distribution round a horse-shoe magnet. A permanent magnet and a current-carrying wire have, therefore, a strong family likeness. In fact, they may be said to be first cousins to one another.

When magnetic flux associated with either two voltaic circuits or a magnet and a voltaic circuit fill or occupy the same space these systems of flux have an action upon one another. This may be expressed by saying that the separate systems of flux lines tend to arrange themselves so that the lines as far as possible run in the same direction, and make themselves as short as possible; in fact, they act in some respects as if they were elastic threads. If, then, one or both of the material objects, whether magnet or wire, which, so to speak, are the vehicles of the flux, are free to move, there will be a movement to promote as far as possible the above-stated tendency of the flux lines. This action is merely an exhibition of a general principle which governs all physical operations, viz., that if any system of material bodies has a different amount of potential energy associated with it in different configurations, it always tends to move so as to render the potential energy a minimum. We can show this tendency of flux lines by three experiments.

In the first place, let a flat rectangular coil of wire, free to move, be connected to a voltaic pile and be suspended by fine wires between the poles of a horse-shoe permanent magnet. The coil will turn so as to place its axis or line perpendicular to its flat face in the direction of the shortest line joining the magnetic poles, and the direction of its flux lines will be from the north to the south pole. This device becomes the means of detecting an embracing flux

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or current in the suspended coil, and is then called a galvanometer.

In the next place, let me draw your attention to two coils of wire, one of which is fixed and the other suspended from a balance. These coils form one circuit which joins the poles of a battery. If they are so connected that the current flows in the same direction in each coil they attract each other; if in opposite directions they repel each other. These actions are the direct consequences of the mutual action of the two systems of magnetic flux associated with the fixed and movable conductors respectively.

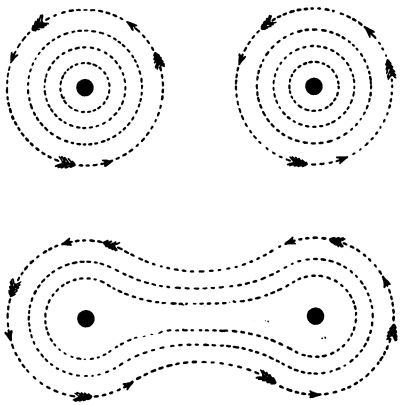

FIG. 5.—Electric Currents in Parallel Conductors flowing in the same direction attract each other.

The whole of the mechanical actions which conductors conveying currents exert on one another, as discovered and investigated by Ampere, may be interpreted in terms of the fundamental qualities of the magnetic flux systems around each and both of the conductors. These actions may be stated to be as follows:—Consider two straight conductors and wires connected respectively to two independent voltaic batteries. Let the end-on view of these conductors be indicated by the small black circles in Fig 5. Each of these conductors separately, if independent, is, as we have seen, embraced by a system of circular concentric lines of magnetic flux, represented by the dotted circles in the upper diagram. The arrow heads represent the direction of the flux. If these systems of flux rotate in the same direction, the currents are said to be in the same direction. Under these circumstances, if the two systems of flux co-exist in contiguity, they merge into one system as roughly shown in the bottom diagram of Fig 5. Part, at least, of the flux system is, then, common

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to the two conductors; the flux lines embracing both conductors have a tendency to make themselves as short as possible. They cannot do this without causing the conductors they embrace to approach. Hence the apparent action at a distance or mutual attraction of the visible conductors may be explained as being due to the action of an invisible system of magnetic flux embracing both conductors. The conductors are simply pulled together by the flux just as two rods would be if embraced by a system of elastic bands in a state of tension. Similarly we may explain the repulsion of two conductors traversed by currents in the opposite directions. If the end-on view of these conductors is represented by the black dots in Fig. 6 and the oppositely directed systems of embracing magnetic flux by the dotted lines. Then in the space between the conductors the flux belonging to each is directed in the same sense. The flux lines under these circumstances are, as it were, squeezed together and exert a mutual lateral pressure on each other. Hence the visible repulsion of the conductors may be interpreted as the result of a lateral pressure

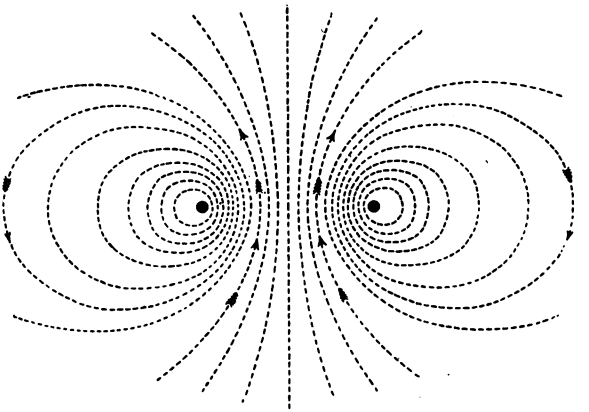

FIG. 6.

between their invisible embracing flux lines which are in the same direction in the interspace between them. The flux lines behave, therefore, as if they had a tendency to contract along their length, and swell out or press each other apart laterally. The action somewhat resembles that of a series of parallel muscular fibres in the animal body, which, when stimulated, contract longitudinally or exert a tension in the direction of their length, but expand laterally and exert a pressure upon each other at right angles to their length.

It is, then, necessary to demonstrate to you that this magnetic flux system round the circuit-closing wire of the Volta pile is a store of energy. It requires an expenditure of energy to produce it, and when produced it is a store of energy which is available for conversion into some other form.

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As an introductory notion it is essential to comprehend that all those substances which we commonly call conductors of electric current have the property of absorbing or dissipating the energy of the magnetic flux surrounding them or linked with them and converting it into heat. The energy represented by the magnetic flux produced round the circuit-closing wire of a pile is continually being absorbed by, and transformed into heat in, the wire. At the present moment we are not acquainted fully with the mechanism by which this is brought about. The quality of the circuit in virtue of which it thus continually absorbs in and transforms into heat the energy of the embracing flux is called its *electrical resistance.* This property of certain bodies is the foundation of all electric lighting and heating. In order to maintain the flux round a wire we have to continually expend energy, and the resistance property of the wire as continually dissipates that energy or changes it into heat. Those substances we usually call good conductors should really be termed bad dissipators.

This dissipative property depends on the absolute temperature of the conductor. There is considerable evidence that at the absolute zero of temperature (−273° cent) all pure metals would cease to have power of dissipating the energy of the embracing magnetic flux constituting an electric current through them, and they would become perfect conductors.

The operation of maintaining a magnetic flux round a metallic wire is in one respect, therefore, very much like pouring water into a cistern with a hole in the bottom.

We can now proceed to an experiment in illustration of the fact that a magnetic flux system is a store of energy. We connect in series with a voltaic pile two parallel circuits (*see* Fig. 7), one part of one circuit consisting of a very long coil of wire of many turns. The other circuits consist of two lamps or carbon filaments having very few convolutions and a short wire whose resistance is equal to that of the bobbin. Across the middle of these parallel circuits is bridged a small glow lamp. If we send a current through the parallel wires the proportions of the

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four sections of the two parallel circuits may be so adjusted that the bridge lamp does not light up, because no current goes through it. But if we switch off or break the connection with the battery the bridge lamp flashes up for one moment, whilst the others go out. This flashing up is due to the discharge through it of the energy which is associated with the magnetic flux surrounding the long coil of wire, the magnetic flux energy being transformed into heat and light energy by the resistance of the lamp filament in the bridge circuit. This experiment

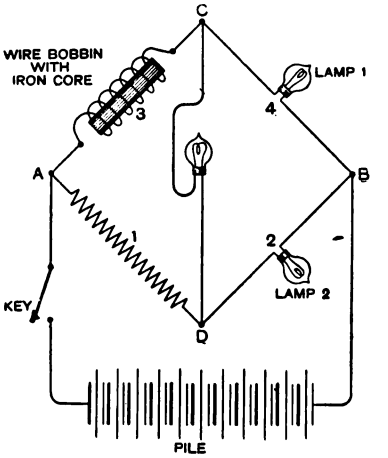

FIG. 7.—The current of the pile has two circuits open to it in passing from A to B. One along the path 3 and 4 and the other along 1 and 2. The former contains a wire bobbin having an iron core, and is said to be an inductive circuit. The latter is a nearly non-inductive circuit. Both circuits have equal resistance. On opening the key in the battery circuit the lamps 2 and 4 go out but the lamp in the bridge circuit C D flashes up for a moment.

shows that when the currents are flowing through the two paths energy must be associated with the system, since on severing the connections with the battery we have an evolution of light and heat as shown by the flashing up of the bridge lamp. This energy is derived from the system of magnetic flux around the circuit of the long wire bobbin.

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In connection with this experiment I must draw your attention to a very important matter. A few moments ago I was speaking of the electric stress which exists between two terminal plates of the voltaic pile, and it was stated that the stress depended to a considerable extent on the nature of the medium in which the plates were placed. Some materials increase this stress or make it greater than it would be in a vacuum. These substances are said to have high *dielectric* power. Exactly in the same way the total magnetic flux round a wire of given length and form connecting the poles of a given voltaic pile depends to some extent on the medium in and around the wire. Some substances, such as iron, nickel, and cobalt, if placed round the wire enormously increase the associated magnetic energy, and they are said to have great *magnetic permeability*.

The study of electric and magnetic phenomena has shown that we are primarily concerned with two physical changes or effects, capable of being produced in matter and also in so-called empty space; these changes are denominated respectively *electric displacement* and *magnetic flux*. It is mentally impossible for us to observe physical effects of the above kind without feeling the necessity for special names for the efficient or active agencies producing them. Hence we employ the terms *electric force* and *magnetic force* to denote the causes, whatever their nature, producing respectively displacement and flux. We then find that the same electric and magnetic force, when acting through various media, produces very different amounts or degrees of displacement or flux, and words are needed to express the displacement or flux produced by a unit of electric or magnetic force. The phrase, *specific inductive capacity*, was coined by Faraday to denote the electric displacement produced by a unit-electric force. It is, however, more convenient to call this the *electric pliability* of the medium.

Again, the term *magnetic permeability* is employed to denote the magnetic flux produced by a unit of magnetic force. Hence we may say that

Electric pliability = Electric displacement per unit of electric force;

Magnetic permeability = Magnetic flux per unit of magnetic force.

The permeability and pliability are thus specific qualities of any medium or substance. These qualities are not, however, independent in magnitude of each other. We know nothing about the absolute values of these quantities, in terms of fundamental dynamical units, for empty space, or rather for the æther filling space, but it can be shown that the product of their values is always, for every homogeneous medium, a constant quantity, and is a measure of the reciprocal of the square of the velocity of propagation of an electromagnetic wave through that medium. In any place where there is electric displacement the electric energy stored up per unit of volume

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is measured by the product of the displacement and the average electric force producing it, and similarly in any place where there is magnetic flux the magnetic energy stored up per unit of volume is measured by the product of the flux and the averag- magnetic force. In other words, the *magnetic energivity* or magnetic energy per unit volume is measured by the quotient of half the square of the flux by the permeability, and the *electric energivity* is measured by the quotient of half the square of the displacement by the pliability. In a quite similar manner the so-called kinetic energy or *motional energivity* of a moving body of unit volume is measured by the quotient of half the square of its momentum by its density. Also, in the case of torsion of an elastic distortable material, the *torsional energivity* per unit volume is measured by the quotient of half the square of the twist or distorsion by the reciprocal of the torsional rigidity.

Two other quantities related respectively to electric and magnetic force are important, and these are called the line integrals of the above forces. The meaning of the term line-integral is as follows: In every place where there is a distribution of electric or magnetic force these forces must have certain directions as well as magnitudes at every point. If any line, open or closed, is drawn in that place and divided up into very short elements of length, we may add together the products formed by multiplying the length of each short element by the magnitude of the force at that place estimated in the direction of the length of the element. This sum or integral is called a line-integral.

The line-integral of magnetic force thus taken round any closed line is called *the total electric current*, or *amperage*, through that loop.

The line-integral of electric force round any closed line is called the *electromotive force* or *voltage* round that circuit.

The names amperage and voltage are derived from Ampère and Volta.

In the experiment just shown the coil of wire had an iron core put into it to increase the total flux round it and therefore the total magnetic energy associated with it under the stated circumstances. If that iron core is removed we shall find much less evidence of energy associated with the coil on breaking the circuit.

Having now pointed out the form of the embracing magnetic flux which surrounds the circuit-closing wire of a Volta pile, and the fact that this flux represents a store of energy, or is in fact energy in a particular form, let me ask you to notice another fact, and that is that this flux behaves as if it had inertia. It cannot be instantaneously reversed in direction.

To show this we use again a divided circuit (*see* Fig. 8), the two sides having equal resistances, one consisting of a wire of few turns, but high resistance (1) in series with an

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incandescent lamp (L2), and the other side of a similar lamp, (L1) in series with a long bobbin of wire, (2) with an iron core. If we pass a continuous current through the duplex circuit, from B to A, we see by the illumination of the glow lamps inserted on both sides that current exists in both sides or parts of the divided circuit. If, however, we employ an alternating current little or none of the current flows through that half of the circuit which contains the coil of many turns with an iron core. The reason for this is that the rapid alternations of electromotive force, which in this case is reversed 200 times a second in direction, do not give time enough to establish the flux round the circuit with the iron core. Hence, there is little or no current in

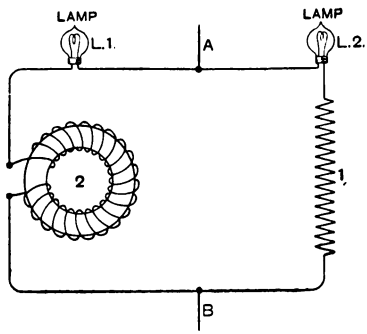

FIG. 8.—The circuit between A and B is duplex. One branch consists of the lamp filament L_1 and the coil (2) with iron core, and is an inductive circuit. The other consists of the lamp filament L_2 and a short wire (1), and is nearly non-inductive.

that circuit, and the lamp does not light up. Accordingly you will now realise that the whirlpool of magnetic flux which exists round the circuit-closing wire of the Volta pile is characterised by three properties:

(1.) It is a store of energy, and energy has to be expended to produce and maintain it.

(2.) It possesses a quality which resembles inertia in that it takes time to be produced or to reverse in direction.

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(3.) It exists all along certain closed lines, and the lines of flux are endless lines exhibiting a tendency to become as short as possible.

These three qualities give it a striking resemblance to a vortex motion or circuital movement in a heavy fluid, such as water circulating round an axis. Hence the appropriateness of the term magnetic flux. That which we are accustomed to call the conductor or wire is merely the axis round which this magnetic flux circulates. The material of which the wire is made has, however, these two marked qualities:

(*i.*) When the flux is, so to speak, circulating round it, the material substance of the wire has the property of absorbing the energy of the flux and dissipating it as heat, in virtue of a property called its Electrical Resistance.

(*ii.*) It offers a certain obstruction to the passage of a magnetic flux line across or through it, so that a flux line does not pass so quickly through a conducting material substance as it does through a vacuum or insulator. The less the resistance of the material the more slowly will the magnetic flux penetrate into it.

The process by which the magnetic flux is established in any region has a certain resemblance to the operation of producing rotation in a mass of liquid contained in a rotating vessel. Suppose a basin of liquid to be placed on a turntable and the vessel set in rotation. It can easily be seen that the process of getting up the rotatory motion in the general mass of the fluid is something as follows:—The fluid in contact with the sides of the vessel has rotation imparted to it by the moving vessel in virtue of the friction between the liquid and the vessel. In consequence of the inertia of the liquid the full motion is, however, not immediately acquired. Similarly, this outer layer of liquid when set in movement gradually imparts motion in the same direction to the next layer of liquid, in virtue of the viscosity of the liquid, and so for succeeding layers. The handing on of the motion from layer to layer of liquid thus proceeds until the whole mass of the liquid is set in motion with the same angular velocity. This propagation of angular velocity inwards is dependent upon viscosity in the liquid, and hindered by its inertia or density. Hence, a dense liquid, such as mercury, will be set more slowly in motion than a less dense but equally limpid liquid. A viscous or sticky fluid, such as treacle, will be more easily set in motion than an equally dense but less viscous fluid.

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Hence, the establishment of equal angular velocity proceeds more rapidly in proportion as viscosity is greater and density less.

In the case of magnetic flux it can be shown that the greater the magnetic permeability of the medium the more slowly is magnetic flux established through it. Also, in proportion as the medium has greater electrical resistance the more quickly is magnetic flux established in it. The establishment of the flux begins at the surface of the medium and is propagated slowly into it, the rate of propagation being slower the greater the permeability and the greater the conductivity of the medium. Hence, if the flux is an alternating flux it cannot be propagated very far into a good conductor, because no sooner has it begun to enter or soak in than it is recalled, so to speak, by being reversed in direction. The higher the frequency or rate of reversal, the less far will the flux penetrate into the conductor.

Hence a very good conductor like copper is an effective screen for alternating magnetic flux, and the higher the frequency the thinner may be the conducting sheet which can act as a practically perfect screen.

Taking the illustration used above of the rotating basin of liquid, we may suppose, for instance, the basin to be merely rocked backwards and forwards round its vertical axis with an oscillating rotatory motion, instead of being set spinning uniformly in one direction. In that case the motion would never completely reach the centre of the liquid. The respective concentric layers, into which we may conceive the liquid divided, would execute an oscillatory motion, rotating first one way and then the other, but the amplitude of motion of each concentric layer would decrease rapidly from the edge to the centre of the liquid. Hence there is a close analogy between the production of angular velocity in a liquid under the action of angular torque when the liquid possesses density and viscosity and the production of magnetic flux by magnetic force in a medium possessing permeability and resistance.

Moreover, just as the viscosity of the liquid is the property in virtue of which any motion set up in it is quickly destroyed and the kinetic energy frittered away into heat, so the electrical resistance is a corresponding quality of the matter in virtue of which the energy of the magnetic flux, when established in and around the conductor, is rapidly converted into heat and so destroyed as flux, when the flux is left to itself. Accordingly, if a system of magnetic flux is established in any way round a conductor, it cannot survive indefinitely. The energy of the flux next to the conductor is absorbed and dissipated, and the flux, so to speak, is destroyed. Then the flux beyond contracts in and is in turn dissipated until the whole magnetic energy has entirely been converted into heat. The power which the conductor thus possesses or dissipating the flux energy depends upon the possibility of the energy of that kind of circuital motion which constitutes the magnetic flux being transferred to the molecules of the conductor, and taken up by them in the form of the vibration, rotation or other motion which exhibits itself to our tactile sense or other tests as sensible heat. It appears probable that, in the case of perfectly pure metals, cooled to the absolute zero of temperature, this dissipative power ceases to exist.

These facts can be easily illustrated in the following manner: If we hold a circuit of wire connected to a

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galvanometer over a magnetic pole or another circuit traversed by a current, and bring the first circuit suddenly nearer to the magnet, we find a transitory current produced in the moving circuit, which is called a *secondary current.* This secondary current only lasts a very short time. On moving away the secondary circuit we obtain a similar momentary current in the opposite direction. This familiar and classical experiment is described in every text-book and exhibited at almost every electrical lecture, but I am not aware of any treatise in which an analysis of its true nature is given.

A suggestion as to the real operations involved may, however, be given by a series of diagrams (*see* Figs. 9, 10, 11, 12), which are intended roughly to indicate the relation of the primary magnetic flux to that round the secondary circuit at different stages. As the secondary circuit advances towards the magnetic pole the divergent system of magnetic flux from the magnetic pole embraces it. The flux lines then wrap round the wire and are finally, so to speak, nipped off, leaving a separated system of flux lines embracing and associated with the secondary circuit. This secondary or detached flux is rapidly destroyed, its energy being dissipated by the resistance of the secondary circuit. The flux belonging to a magnet or primary circuit, by being moved across or caused to "cut" a second circuit, thus gives birth to another system of flux, called the secondary flux or current, which has a transitory existence. Instead of moving either of the circuits we may employ an alternating magnet or primary flux and we then obtain an alternating secondary current in the secondary circuit. This secondary current may be strong enough to illuminate a small glow lamp in the secondary circuit. You will be able then to notice that this alternating magnetic flux penetrates quite easily a piece of wood or sheet of zinc, but cannot pass through a good conductor or plate of small resistance, such as a thick sheet of copper. The

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reason is that its direction is being reversed so rapidly that it has no time to get through to the other side of the good conducting copper.

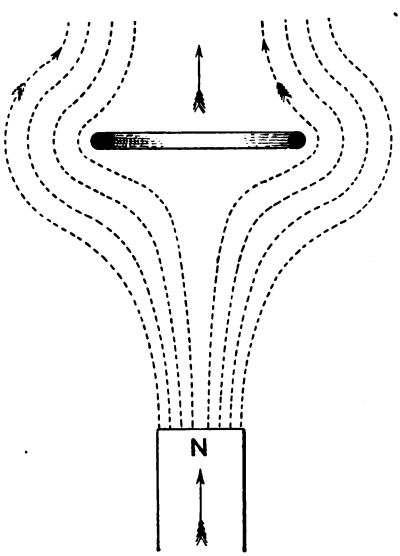

FIG. 9.

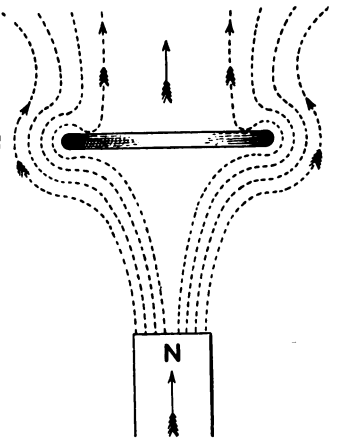

FIG. 10.

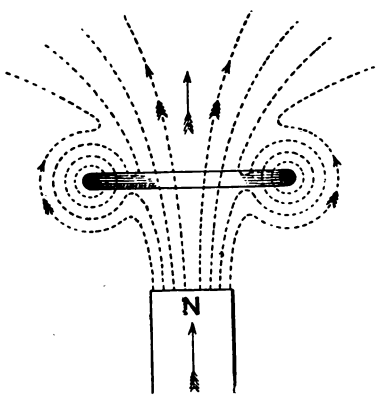

FIG. 11.

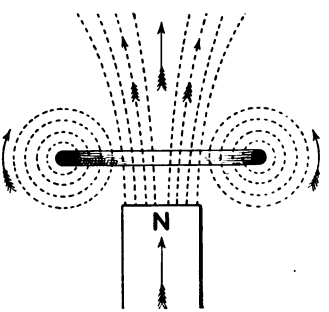

FIG. 12.

FIGS. 9, 10, 11, 12.—Diagrams roughly illustrating the disposition of Magnetic Flux Lines created round a Conducting Ring (shown in section) as it is approached by a permanent Magnetic Pole N. The four diagrams represent four stages in the approach of the magnet. The independent flux system created constitutes the secondary or induced current in the ring.

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When we are thus employing an alternating current to produce a secondary alternating current in another circuit, it is found that the secondary current is at every moment opposite in direction to the primary current.

It is not difficult, by the aid of a simple diagram, to see that the above follows at once from the principles already explained, viz., that there is a certain sluggishness in a magnetic flux combined with the fact that it is only by changes in the amount of the magnetic flux penetrating

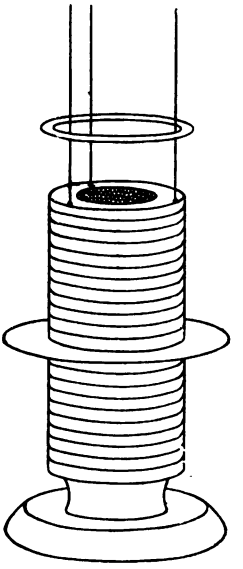

FIG. 13.—Aluminium Ring projected from the Pole of an Alternating Current Electromagnet and floating over the Pole when restrained by three strings.

the secondary circuit that any secondary localised flux round can be produced. If we bear in mind an experiment, shown a few moments ago proving that currents in opposite directions repel one another, it will be seen at once that there should always be a repulsive force between a primary circuit and a secondary circuit, at the moment when the secondary current or flux is generated in the latter. That

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this is so can be illustrated in a striking manner by an experiment due to Prof. Elihu Thomson.

If we place an aluminium ring over an alternating current electromagnet, and excite the latter with a powerful alternating current, we make a very vigorous alternating magnetic flux which penetrates the aperture of the ring. The ring then jumps up into the air (*see* Fig. 13). Falling down again it floats, as you see, upon an invisible cushion of magnetic flux. The ring, however, soon becomes very hot in consequence of the powerful secondary current

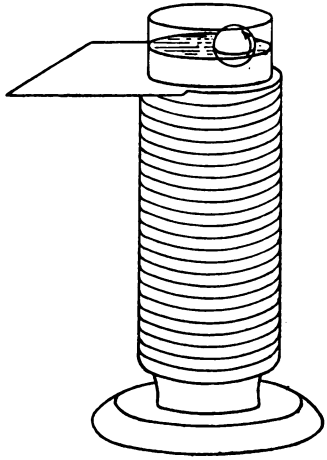

FIG. 14.—Hollow Copper Ball floating in water over an Alternating Current Electromagnet, and caused to rotate by the interposition of a "shading" copper-plate.

generated in it. That there is such a current is proved by trying the experiment with a broken ring, which, as you notice, will not jump. Rings of copper will also jump, but are less nimble than rings of aluminium, and rings of brass will hardly jump at all.

We may illustrate the effect of the material of the ring by putting all the rings on a paper tube over the magnetic pole. In this case they float in the air at different heights. A thick copper plate, weighing several pounds, can in this

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way be made to float in the air upheld by the repulsive force exerted on it in virtue of the secondary currents generated in it.

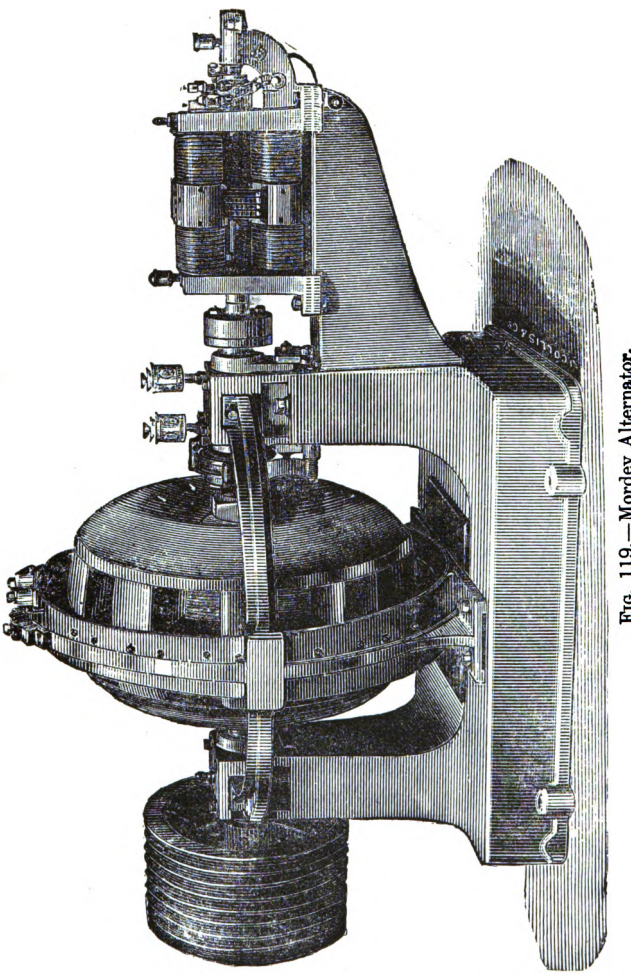

Fig. 119.—Mordey Alternator.

Another interesting experiment due to Professor Elihu Thomson is the rotation of a copper ball floating in water when placed over an alternating magnetic pole. The ball

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rotates or spins round if we shield one-half of the ball by a thick copper plate, and so render the repulsive force on the ball lopsided or unsymmetrical (*see* Fig. 14). Copper wheels in the same way revolve over a half-shielded alternating magnetic pole.*

The above experiments are all illustrative of the effect of a varying or changing magnetic flux in generating a secondary flux around another adjacent circuit. The very

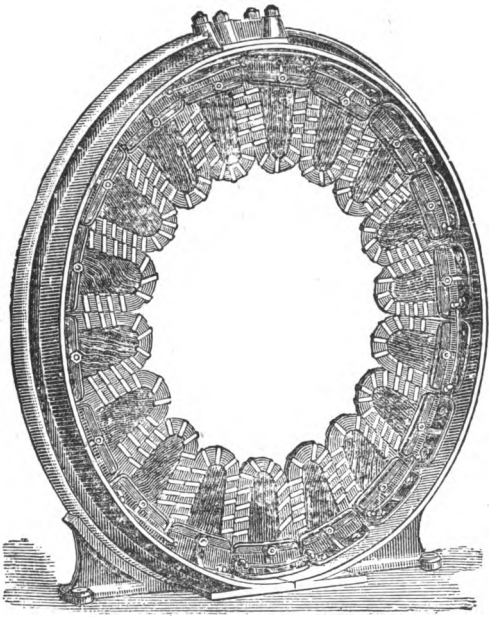

FIG. 16.—Armature of Mordey Alternator.

currents which we are using for our experiments, provided for us by the kindness of the Dover Electric Lighting Company, are generated in this manner. About a hundred yards from this hall is the Company's generating station. In this station are certain machines called Mordey

* The reader desirous of obtaining additional information on these electro-magnetic repulsion effects is referred to a treatise on the "Alternate Current Transformer" by the author, p. 307, Vol. I.

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alternators. These alternators (*see* Fig. 15) are constructed somewhat on the following principle: To the inner circumference of an iron circular frame are attached a number of flat coils of wire joined up in series. The coils constitute a circuit called the armature circuit (*see* Fig. 16). This armature is placed between the poles of, and embraced by, a peculiar-shaped magnet (*see* Fig. 17) having a number of claw-shaped north poles on one side and an equal number of south poles on the other. The number of magnet poles

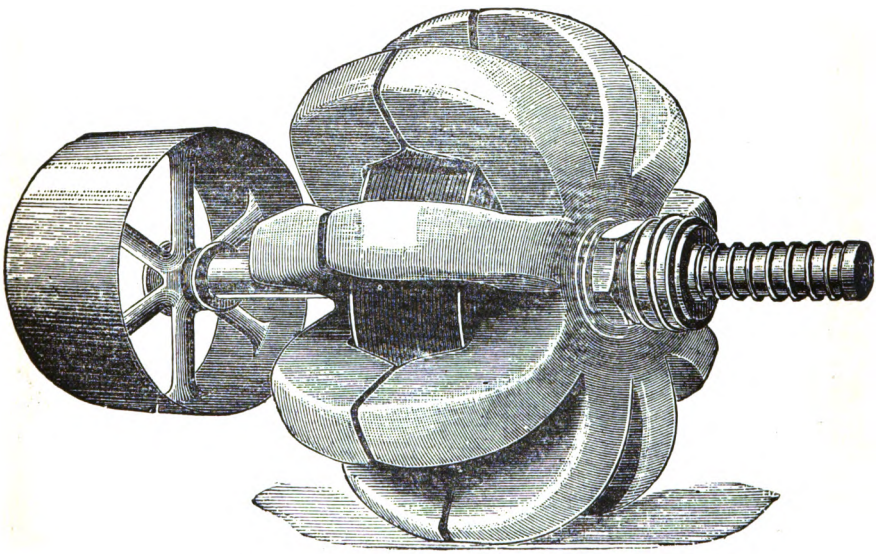

FIG. 17.—Field Magnet of Mordey Alternator.

on each side is equal to half the number of armature coils. When the magnet is made to revolve, the stream of magnetic flux lines which proceeds from each north pole to the adjacent south pole is alternately inserted into, or withdrawn from, each coil or flat bobbin and the flux-change accordingly creates an electromotive force in each coil and an alternating current in the coil or armature circuit.

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In practice the electric current so generated has generally an electromotive force or pressure of 2,000 volts, as it is termed, and such pressure is too high for use with incandescent lamps. The alternating current is therefore passed through an appliance called a transformer, one of which we have at the back of this platform. This transformer (*see* Fig. 18) consists of an iron ring, on which are wound two circuits or wires, one having many more turns than the other. The alternating current from the alternator passes

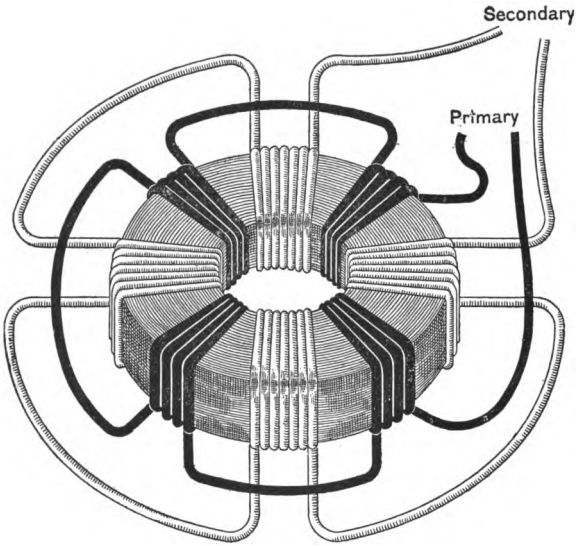

FIG. 18.—Typical closed Circuit Alternating Current Transformer.

through the circuit of many turns and generates another alternating secondary current of lower electromotive force in the circuit of fewer turns. The iron core, by its large permeability, causes the creation of a large amount of magnetic flux, which at each alternation is linked and unlinked with the secondary circuit. The transformer therefore enables us to employ a small electric current to produce another much stronger or larger one; it effects this change, not by creating energy, but at the expense

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of a reduction in what is called the pressure of the current.

This appliance can be used or constructed in another way. If we have two coils of wire, one consisting of a few turns of thick wire and over it one consisting of many miles of very fine wire, we have an instrument called an Induction Coil. You have already seen that the starting or stopping of a current in the one coil will give birth at that moment to another current in the other coil, called a

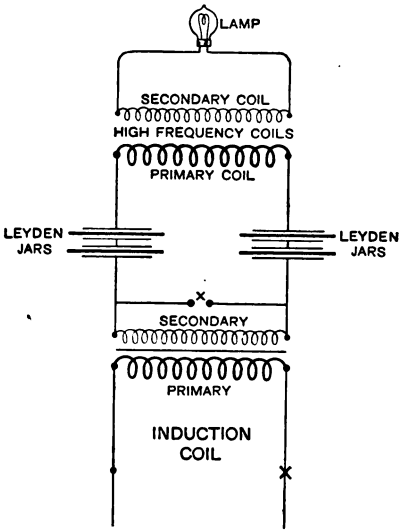

FIG. 19.

Arrangement for Generating a High-frequency Alternating Current by the Oscillatory Current of a Leyden Jar Battery Charged by an Induction Coil.

secondary current. Such an apparatus is on the table before me. If the secondary circuit is not closed, the starting and stopping of the primary circuit gives rise merely to an electromotive force in the secondary coil. The secondary circuit is for the moment exactly in the same condition as an exceedingly long Volta pile, the circuit of which is not closed. We can, therefore, employ this induction coil to create an electrostatic strain in a suitable

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material. With this apparatus I have it in my power to illustrate to you many of the facts concerning electric currents, and in particular to produce alternating currents of very great frequency, viz., about one million per second. It will, therefore, be desirable to explain a little in detail the arrangements.

Through the primary circuit of an induction coil (*see* Fig. 19) is passed a current from a voltaic battery which is interrupted about 1,000 times a second by a Wehnelt high-speed break. This interrupted primary gives rise to an interrupted high electromotive force in the secondary circuit of the coil. To the ends of the secondary circuit are attached the interior coatings of a set of Leyden jars, which are in effect sheets of glass coated with tinfoil on each side. This high electromotive force or stress produces an electrostatic strain in the glass, and that strain is a store of energy. Two discharging balls (X) are arranged across the terminals of the secondary circuit, and when this strain reaches a certain value the air insulation between the balls breaks down and an electric spark passes between them.

One point it is essential here to explain very clearly. The air and all other gases at ordinary atmospheric pressures can endure a certain maximum electric strain produced in them and remain up to that point very good non-conductors or dielectrics; if, however, the electromotive force exceeds a limiting value, the air or gas passes immediately into a highly conductive condition. This property of passing instantly from a non-conductive to a conductive condition under a certain critical electric stress is a characteristic property of gases at ordinary pressures. In the arrangement before us the outside coatings of the Leyden jars are united by a wire wound on a wooden frame. Hence, when the air gap breaks down into the conductive condition we have a circuit (*see* Fig. 20) composed of this wire on the one side, the conductive spark gap on the other, and these are separated by

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two glass plates or condensers in a state of electric strain in opposite directions. This electric strain is in effect an electromotive force. It was produced by an electromotive force, and it is in turn, when produced itself, a source of electromotive force; just as a spring can only be stretched by a mechanical force and when stretched is itself a source of mechanical force.

Hence, the electrically strained glass, releasing itself, begins to produce round the circuit a magnetic flux embracing it, —that is to say, it produces in the circuit an electric

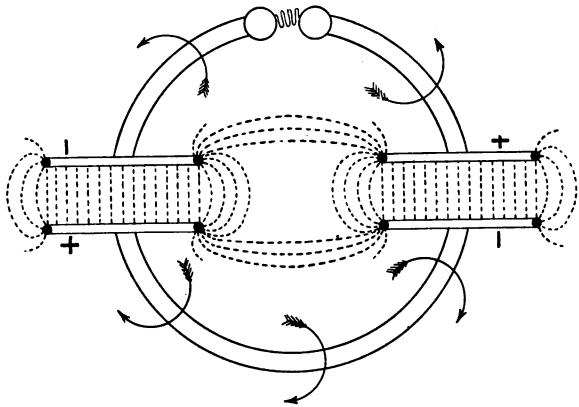

FIG. 20.—Electrical Condition of the Leyden Jar Circuit at the Moment when the Spark Passes Between the Discharging Balls. The Dotted Lines represent the direction of the Lines of Electrostatic Strain and the Arrows the Lines of Magnetic Flux.

current. Owing, however, to the inertia-like quality of the magnetic flux, this flux or current cannot be produced at once, and when produced it cannot be annihilated instantly. The flux when generated persists and expends its energy in charging up the condensers in an opposite direction—in other words, its energy passes back into energy of electric strain, and the process of creating the flux or current is then again repeated, and so on until the energy of the original electric strain is all frittered away into heat. Accordingly we

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have in the wire connecting the outsides of the condensers an enormously rapid alternating current, and a current having a frequency of about a million a second is now being produced in the large circuit attached to a battery of twelve Leyden jars on the table before me. It can be proved at once that there is in the wire an alternating current, because if we place near this first wire carrying the high-frequency current another secondary circuit having included in it a small glow lamp, you see at once that the lamp lights up when the secondary circuit is placed near the primary circuit even when it is more than a yard away (*see* Fig. 21).

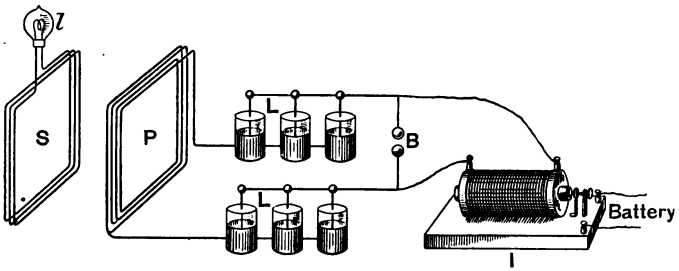

FIG. 21.—Apparatus for the production of a High-frequency Electric Current, I Induction Coil, L L Leyden Jars, B Discharge Balls, P Primary Coil receiving Oscillatory Discharge of the Leyden Jars and S Secondary Circuit in which a Low-tension High-frequency Current is set up.

The whole space for an immense distance round this high-frequency primary circuit is therefore filled with a tornado of alternating magnetic flux, which renders itself evident by creating secondary currents in all closed conductors near it. We can also show you that this flux passes quite easily through a wooden board, but is stopped by even a thin sheet of perforated zinc.

We may with this apparatus perform an interesting experiment to illustrate that the approximation of the turns of the wire of a coil to one another greatly increases the obstruction offered to the passage of an alternating circuit through it. If a coil of insulated wire is inserted in series

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with the secondary circuit, the turns of which can be approximated to each other, we find that the closing up of the coils extinguishes the lamp in the secondary circuit. This is obviously because the flux round each turn of the coil produces a flux—that is, a current, in adjacent turns in opposition to itself, and so the resultant flux is destroyed by the antagonistic action of the different elements of the circuit.

If, instead of employing a closed secondary circuit of a few turns, we make use of a secondary circuit of many turns wound over a primary circuit conveying a high-frequency alternating current, we have an arrangement, called a high-frequency induction coil. This high-frequency coil, as you may now observe, has produced in its secondary circuit an exceedingly high alternating electromotive force of great frequency, and it is possible to create by its use an alternating electrostatic strain in the air of such intensity that the air itself becomes luminous if somewhat rarefied. If we cause this high-frequency electromotive force to operate upon a long column of rarefied gas, in a so-called vacuum tube, the gas column traversed by the alternating current becomes brilliantly luminous. By connecting the terminals of the secondary circuit of the high-frequency coil to two large sheets of zinc gauze we can produce in the interspace a powerful field of electric stress which alternates or changes its direction in this case at least one million times per second. Glass bulbs or tubes filled with rarefied gases become luminous when placed in this alternating electrostatic field.

In connection with this apparatus I wish to draw your attention again to the transformations of energy we see here taking place, and the manner in which electric and magnetic energy are convertible one into the other. In the first place, in connection with the ordinary induction coil, we have an intermittent magnetic flux round the primary circuit which creates in the secondary circuit, when that last circuit is complete, another intermittent

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or alternating magnetic flux; but when the secondary circuit is not complete, creating also between its open terminals, or in the dielectric of the Leyden jars connected to the terminals, electrostatic strain—or, as it is called, electric displacement. This dielectric stress is a form of energy, and when released it can itself in turn produce a magnetic flux round a conducting circuit. In the next place, in the circuits of the high-frequency coil, we have a similar set of energy transformations.

In modern language the electrostatic stress is generally spoken of as potential energy and the magnetic flux is regarded as kinetic energy. The first has a strong analogy to the energy represented by the distortion of elastic matter, the latter to the energy represented by matter in motion. We here tread on difficult ground, and in fact in the decision whether a given form of energy shall be called kinetic or potential much depends upon the assumptions we make as to the nature of the underlying mechanism.

It is usual to classify various forms of energy under the headings of *potential* and *kinetic* energy. These terms are not, however, very expressive. In studying the modes of association of energy with mechanical systems we are led to see that energy exhibits itself either as *motional* or as *configurational* energy. That is to say, it appears in connection with relative motion between the parts of a material system, and also in connection with relative strain or displacement of parts. Strain or displacement of the parts *per se* does not, however, necessarily involve an energy storage, unless the production of the strain is accompanied by the appearance of that which is commonly called a force or stress—that is to say, unless there is a tendency in the produced strain to disappear, if the system is left to itself. Hence we may state that not all configurational changes in a material system are accompanied by energy changes or exhibitions of energy, but only those strains which tend to disappear if left to themselves. It may perhaps ultimately be found that all energy is in reality motional.

A material system, which neither as a whole nor in any of its parts is in motion, is essentially in a non-evolutionary condition—that is to say, nothing is happening in it. The appearance of motion in any way involves progressive changes and phenomena, and the agency lying at the basis of all phenomena-production we call energy. It may therefore be the case that physical energy is only one presentation of some larger all-embracing cause of cosmical phenomena the other aspect of which involves the phenomena that we call mental, especially those of volition. It appears to be impossible for us, in the present state of our faculties, to rest satisfied with any analysis or explanation of a

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physical effect which is not ultimately a dynamical or mechanical one, and this fact is not without significance in our interpretation of mental efforts to penetrate behind the facts of nature.

Up to the present moment you will notice we have been dealing with effects which show us that what we call an electric current depends upon the association of two forms of energy with material substances and circuits of certain kinds which act as their vehicle. One of these forms of energy, namely, the electric, is probably configurational; and the other, the magnetic, is motional; the strain and the motion existing in the medium surrounding the circuits. In the generality of cases this associated energy does not part company, so to speak, with its defining circuit. If we move about a circuit, carrying what we call an electric current, wherever the wire is, there also in the neighbourhood is the chief part of the energy of the associated magnetic flux and electric strain. The brilliant researches of Hertz showed us however that, when alternating currents of very high frequency are set up in an open or unclosed circuit, the energy may be conveyed entirely away from the circuit into the surrounding space in the form of *electric wave*. To arrive at an understanding of the meaning of this expression, I must remind you that a wave in physical language is any periodic change taking place in a material medium of such a character that at any one point a cycle of operations is performed, and at places equi-distant (called a wave length) identical operations are being performed at the same time.

In order that this may take place the medium must possess two qualities: First, it must elastically resist some change being produced in it. Secondly, it must possess an inertia quality: such that a change of this type made in it tends to persist or to go on increasing. For example, consider the case of waves produced on the surface of the sea. The water resists being made unlevel and it possesses inertia, so that when set in motion it continues moving. Hence if raised up or depressed at any point it returns to its original

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level, but in so doing it overshoots the mark and a restoring force is then applied to it in the opposite direction. The same thing is shown in the case of a row of heavy balls tethered to each other by elastic bands, when the last ball has an oscillation imparted to it. The motion is then handed on from ball to ball, and finally reaches the end member of the series.

In dealing with the electromagnetic properties of the space round the Volta pile and its circuit-closing wire we have seen that there are two qualities present: one, called the electric pliability, analogous to the elastic yielding to a distorting force in the case of a solid, and the other, called the magnetic permeability, having resemblance to inertia. We have seen that electric force can create in dielectrics a strain or state called electric displacement, and this strain disappears after the electric force is withdrawn. Also we have noticed that a state called magnetic flux created by magnetic force tends to persist in virtue of a certain inertia-like quality when created. Moreover electric displacement, *whilst it is being produced or destroyed*, brings into existence magnetic flux, and magnetic flux, when increasing or diminishing, creates electric displacement.

The method by which this transformation of energy is effected can only be hypothetically described in terms of some mechanical theory as to the structure of the electromagnetic medium. We have reasons for believing that both electric displacement and magnetic flux can take place in a perfect vacuum, or space devoid of any trace of material substance, and also that every cubic inch of space so filled with strain or flux represents a certain definite storage of energy. Hence, we are compelled to postulate a material or rather super-material vehicle for this energy. Most material systems with which we are acquainted seem to have the power of taking up energy in a motional as well as a configurational form; for if the strain which constitutes the change in configuration is one which tends to disappear when left to itself, it must generate motion; and hence, in virtue of the law of conservation, produce motional energy. Consider a very simple illustration: Let a flat strip of steel have a heavy mass like a pendulum bob fixed at the lower end, and let it be suspended from the top end vertically. If the mass is twisted round, the flat spring is deformed and configurational energy is bestowed upon the system. If left to itself this strain begins to disappear, and as the bob is set in rotation by the disappearing strain, it acquires in virtue of its mass or inertia, a motional energy. Hence, the system left to itself exhibits an alternating transformation of energy;

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the energy at one moment is configurational, due to strain, and at the next moment it is motional, due to inertia and movement. In the same manner the electromagnetic medium, having the two qualities of magnetic permeability, analogous to density or inertia in matter, and electric pliability, analogous to deformability in matter, can exhibit exactly the same modes of storage and transformations in energy. Thus, if the dielectric in a condenser is electrically strained, and if the condenser plates are connected by a metallic circuit of low resistance, and the system left to itself, the energy originally imparted to the system alternates in form. At one moment it exists as energy of electrostatic strain in the dielectric, and at the next as energy of magnetic flux round the circuit, the cycle of energy transformation being continually repeated. We have, however, much yet to learn before we can trace out the precise nature of the configurational changes and motions in the medium which respectively give rise to the two forms of energy we call electric and magnetic.

For a fuller discussion of these questions the advanced reader is referred to the three remarkable Papers by Dr. J. Larmor in the *Transactions* of the Royal Society of London for 1894, 1895 and 1897, entitled "A Dynamical Theory of the Electric and Luminiferous Medium."

We can therefore trace a close analogy between the inertia of ordinary matter and the quality called magnetic permeability, and also between the elastic deformability of matter and its electric pliability or power of permitting in it electric displacement. Hence it follows that a very suddenly applied or removed electric force should create an electric wave in a dielectric just as a very suddenly applied or removed mechanical force will create a mechanical wave in air or water, or other medium possessing resilience of form and inertia. The explosion of a gun or the splash produced by dropping a stone into water are familiar instances of the above fact.

We can also illustrate the production of an oscillation by the very sudden withdrawal of an obstruction to the motion of a heavy body elastically displaced by means of the following experiment: In a U-shaped tube is placed some mercury. If the air pressure is increased above one side of it we displace the mercury. If the air pressure is released very gradually, the mercury comes back slowly to its initial position and without vibration. If, however, the air pressure is released very suddenly, the mercury returns to its original position after a series of vibrations. This illustration is a very important one, because it shows us

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that sudden release from constraint in the case of a body possessing inertia and elastically displaced can produce oscillation.

An exactly analogous effect can take place in electrical phenomena. If two metallic bodies, say rods, are joined to the terminals of an induction coil, then at the moment when the electromotive force is produced in the secondary circuit, the rods are brought into a different electrical condition or to different potentials, and the space between them is electrically strained (*see* Fig. 22). At a certain intensity of strain the air insulation breaks down and it becomes a conductor.

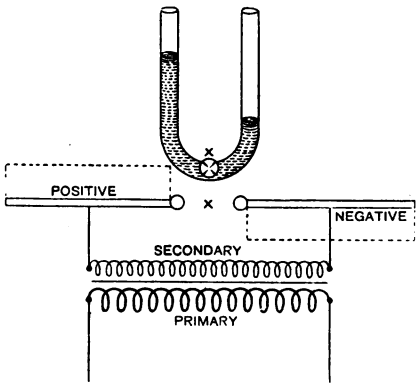

FIG. 22.—Diagram showing the arrangement of an induction coil and spark-balls forming a Hertz oscillator. The **U** tube over the spark balls is merely to illustrate the manner in which the sudden production of conductivity at the spark place × corresponds to opening suddenly the tap in a **U** tube and thus setting the displaced fluid in it in vibration.

This quality of passing quite suddenly from a non-conductive to a conductive state under the action of a critical electric pressure is a very peculiar and important characteristic of gaseous substances. This change is a very sudden one, and the result is that we have set up round the rods an oscillatory magnetic flux, the original energy of strain in the dielectric passing rapidly from the state of electrostatic strain between and around the rods into the form of energy of magnetic flux embracing the rods. Under these

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circumstances it is found that a large part of the energy imparted to the system travels away into space in the form of *an electric wave*, just as, in the case of a tuning fork set in vibration in the air, the mechanical energy is conveyed away, producing an air wave.

In the next place we have to point out how we can detect this radiated electric energy. Time will not permit more than a brief reference to one method.

The construction and operation of a *Hertz Oscillator* for producing an electric wave is as follows :—An ordinary induction coil, preferably one capable of giving an eight or ten inch spark in air, has its secondary terminals connected to two spark balls which form the terminations of two long rods (*see* Fig. 22). If a current is passed through the primary circuit of the induction coil and then suddenly interrupted it creates, as we have seen in the embracing secondary circuit, an electromotive force. Hence, whilst the magnetic flux constituting the primary current is being withdrawn or unlinked from the secondary circuit, this last has an electromotive force of high value produced in it. The rod in connection with one terminal of the secondary circuit is thus raised to a high positive potential and the other lowered to a negative potential. The air between the balls remains a dielectric or non-conductor and lines of electrostatic strain or electric displacement stretch from all parts of one rod to corresponding parts on the other rod. When, however, the potential difference and therefore strain exceeds a certain critical value, the air along a definite line connecting the two balls passes suddenly into a conductive condition. As a conductor cannot support dielectric strain, the electric strain lines are destroyed along this line and those beyond begin to collapse inwards, being as it were successively swallowed up and dissipated in the conductive path. Part of their energy is expended in rendering the air molecules along the conductive path luminous, forming what we call the electric spark. The greater part of the energy, however, re-appears in another form, viz., as magnetic flux round the rods and spark path. The electrostatic strain lines must be considered to collapse in from all sides on the spark line, and this sideway movement results in the generation of concentric lines of magnetic flux, the direction of the magnetic flux being everywhere perpendicular to the direction of the electric strain line and to the direction of motion of the latter. This part of the process consists then in the gradual disappearance of the energy of electric strain and its replacement by nearly an equivalent of magnetic energy. A current is thus established along the rods which, during the time of existence of the spark, are practically one long conductor. This circuit being, however, a non-complete metallic circuit the current can only exist by producing again electric strain in the surrounding dielectric. This strain is in the reverse direction to that which initiated the flux. Hence the flux is gradually destroyed, and the dielectric strain reproduced. The process is continually repeated, but at each oscillation some energy is frittered away into heat in the circuit. By far the larger part, however, is carried away into the medium as wave or radiant energy. A perfect mechanical analogy

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may be found by considering the case of a steel strip fixed in a vice at one end. Let the strip be bent. This involves conferring on it configurational energy, and corresponds mechanically to the production of the dielectric strain. Let the strip now be suddenly released. The strain begins to disappear, and the strip is set in motion. Owing to its inertia it overshoots its original position of rest, and at that moment all its energy is motional. This motional energy corresponds to the magnetic flux energy. The motional energy, in virtue of inertia, gradually reproduces energy of configuration or strain in the strip in the reverse direction to that originally imparted to it, and this again is in turn converted into motional energy. At each vibration some of the original energy is dissipated by heating the strip, but if the vibrations are sufficiently frequent a great deal of the energy is carried away by the production of a sound wave in the air, and the vibrations are therefore more rapidly destroyed. Hence a good oscillator or radiator, whether sonorous or electric, has its oscillations quickly damped out.

In the case of the Hertz oscillator we are considering, probably not more than two or three, or at most a dozen, oscillations take place before all the energy of the system is radiated.

It has been known for a long time, certainly for twenty years, that tubes full of powdered metals were very curiously sensitive to electric sparks, and that a mass of metallic filings behaves like a gas in this respect, that under an electromotive force of a critical value it passes from a non-conductive to a conductive condition.

It was discovered by Prof. D. E. Hughes in 1879—although unfortunately not published at that time—that a tube full of metallic powder, which we will call a *sensitive powder tube*, could thus be transformed from a very bad conductor to a very good conductor by making electric sparks near to it. Facts in science have often to be discovered many times over before their full significance dawns upon the world, and it has been so in this case.* This simple fact about metallic powders was re-discovered by Prof. Calzeechi Onesti, in Italy in 1885, but much more fully examined and investigated in 1891 by Prof. E. Branly, to whom we owe the greater part of our accurate knowledge

* Prof. Hughes' remarkably interesting experiments on what is now called "wireless telegraphy" remained for twenty years unknown to any but a small circle of acquaintances. The description he himself gave of them in *The Electrician* for May 5th, 1899, shows that he had obtained at that date true æther wave effects and detected them by a metallic microphone or sensitive tube. It is much to be regretted that they remained so long unpublished.

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on the subject. Prof. Lodge independently discovered the welding power which an electric spark exerts on two metallic rods or balls in very close proximity, and christened the arrangement a "coherer."*

The behaviour of a sensitive powder tube to electric sparks can quite easily be shown by connecting a sensitive powder tube in series with a galvanometer and a voltaic cell, and then making in the neighbourhood of the arrangement an electric spark. We find that at every spark the non-conducting mass becomes a conductor, but can be brought back again to its original condition by a slight tap or shake. Moreover it has been found by Signor Marconi that a long vertical wire attached to the sensitive powder tube has the property of increasing enormously the distance at which it can feel the effect of an electric spark.

These principles have received their most logical extension and completion in the evolution of the electro-magnetic wave telegraphy which Signor Marconi has developed on such a large scale in the last few years. The chief principle which underlies this industrial application of research is that the sensitive powder tube, when passing into the conductive condition, can be made to complete another voltaic circuit and so operate any ordinary form of telegraphic instrument. By sending long and short impulses to act upon the sensitive powder tube, and keep it for a longer or shorter time in the conductive condition, any of the ordinary forms of telegraphic instrument can be operated at a distance by the action of a local battery.

The arrangements employed by Marconi have been so frequently described that there is no need to enter into details.† He has so far found that, for long

* It has recently been discovered by Prof. J. C. Bose, of Calcutta, that under the influence of an electric wave, the electric conductivity of loosely pressed pieces of *potassium* is decreased instead of being increased, as in the case of most other metals. Also that there is a spontaneous return to the original condition when the wave ceases. It is evident, therefore, that the term *coherer* is not applicable in this case, and in many respects is a term which implies more than it is advisable to assume.

† For a technical account the reader is referred to a Paper by Signor G. Marconi, read before the Institution of Electrical Engineers, March 2, 1899. (See *Proc.* Inst. Elec. Eng., 1899.)

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distance work a sensitive powder tube, formed with a mixture of silver and nickel filings, held between silver rods with their ends very slightly amalgamated, gives the best results (*see* Fig. 23). The interspace between the silver rods in his tubes is not more than a millimetre. The air in the tube is nearly all removed. In making a sensitive tube for telegraphic purposes an important element in success is to secure quick return to the non-conductive condition, with certainty and quickness after each signal has been received. Another important element of Marconi's arrangement of apparatus is the introduction of

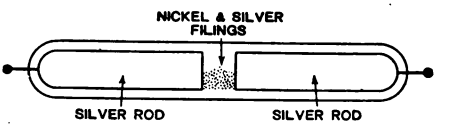

FIG. 23.—Marconi Sensitive Powder Tube.

inductive coils, between the sensitive tube, relay and battery (*see* Fig. 24). These inductive coils prevent the rapidly-oscillating current produced in the sensitive tube circuit from being shunted partly round the battery and relay circuit, and compel all the wave energy taken up by the receiving rods to expend itself in causing the metallic powder to pass into the conductive condition. The finely powdered metal in the sensitive tube behaves towards electromotive force just as does air or any other gas at normal pressure. That is to say, if a

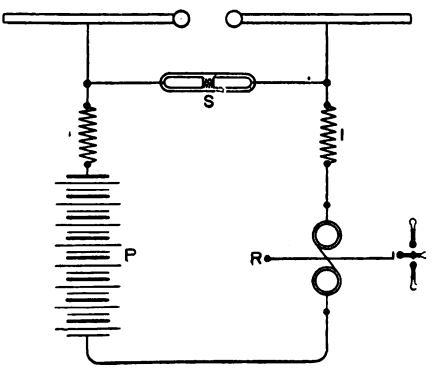

FIG. 24.—Sensitive Powder Tube S in Series with Battery P and Relay R and Inductive Coils I I.

voltage or potential difference is created between the ends of the tube, below a certain limiting value the finely divided metal remains a di-electric or non-conductor. If, however, the electromotive force is made to exceed a critical value the powder passes at once into a conductive condition, in which state it, of course, permits the local battery to send a current through it and through the relay in circuit with it.

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Hence, by sending from the transmitting station electric waves we are able to close at pleasure the circuit of a local battery, and operate another circuit-closing device called a relay. This relay is then made to work an ordinary telegraphic printing instrument.

The function of the long receiving rods appears to be as follows: The sensitive tube requires to have applied to it a certain electromotive force to break it down into the conductive state. The electric force in the space round the tube which has arrived there by wave propagation from the transmitter is more feeble the greater the distance from the oscillator, but by placing two long metallic wires in a direction parallel to this electric force and inserting the tube between them these rods add up or integrate the feeble electric force in the direction of their length into a sufficiently great electromotive force to effect the required transformation. Bearing in mind that the electromotive force is the line integral of electric force, it is easily seen that we can, so to speak, compensate for feeble electric force by employing a sufficiently long wire or rod. Hence, the further apart the receiving and transmitting stations the longer must be the rods. Also the longer the rods in connection with the transmitter the greater is the inductance and capacity of the oscillator, and the greater the energy which is, therefore, taken up from the coil and radiated at each spark.

Marconi has found, by practical experiment, that, with a given type of sensitive tube, the distance at which signals can be read varies as the square of the height of the rods. He also employs only one pair of rods placed vertically, the other ends of the sensitive tube and corresponding spark ball being connected to the earth.

It has been frequently asserted that the practical utilisation of æther waves in wireless telegraphy would be limited by the difficulty of transmitting them through rock masses, buildings and other material obstacles. Experiment, however, proves that this is not the case, at least with the very long waves employed by Mr. Marconi. An exceedingly interesting experiment to illustrate this non-interference was tried on August 16th, 1899, at Dover, between the Dover Town Hall and the South Foreland. The Town Hall at Dover stands in the centre of the town and is surrounded by high cliffs. The Castle Rock rises on the east side to more than 400 feet above the level on which the Town Hall stands, and a continuous chalk cliff extends between the Castle and the South Foreland for a distance of four miles. At this latter place is one of the signalling stations of the Wireless Telegraph and Signal Company, and a mast and signalling wire, 150 feet high, was established there in April, 1899, for experimental purposes, for communication between the South Foreland, the East Goodwin Lightship and a station at Wimereux, on the French coast. At the suggestion of the author the Wireless Telegraph Company kindly undertook to make an experiment as follows:—The Town Hall tower is about 65 feet in height, and on this tower a flagstaff, some 45 feet high, is erected. A signalling wire was attached to this flagstaff, and the end brought down into the hall. Employing the Marconi apparatus it was then found that not the slightest difficulty existed in communicating, through or over the Castle Rock, with the station at South Foreland, and even with the Goodwin Lightship 12 miles beyond. The immense mass of chalk cliff lying between the Town Hall, Dover, and the South Foreland, appears to offer not the slightest obstacle to the

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passage of æther waves to or from the wire attached to the Town Hall flagstaff. The above described experiment only confirms many others made by Mr. Marconi, all of them showing that rock masses of very considerable size intervening between two stations do not in the least affect the freedom of communication by æther wave telegraphy.

It must be obvious to you that the moment we have it in our power to close the circuit of a voltaic battery by merely making an electric spark at a distant place, innumerable applications at once suggest themselves. One of the latest and most ingenious of these is a method of steering self-moving torpedoes by means of an electric spark and sensitive powder tube which enables the movements of the deadly weapon to be controlled by an operator at a distance.

To us at present the interesting question, however, is to discuss briefly the mode by which the electric spark produces this effect at a distant place. The classical investigations of Hertz showed clearly that we are concerned here with a wave motion. The oscillatory spark and current in the radiator produce an electric wave in space—that is to say, they produce a periodic electric displacement at any point, and this displacement is cyclical and passes through a cycle of values. Also it is accompanied by a periodic magnetic flux, the flux being at a maximum when the displacement is passing through its zero value, and, conversely, the instant of zero magnetic flux coinciding with that of maximum displacement. Identical operations are being simultaneously performed at places distant by a wave length.

A convincing proof that any transfer of energy is effected by a wave motion is given if we can produce *interference* —that is to say, if an effect or disturbance starting from a common source can be caused to divide and then proceeding along paths of different lengths can be made to destroy itself at certain points. In the case of waves of elevation and depression on water, waves of compression and rarefaction in air or sound, and waves in æther constituting light, it is a familiar fact that this interference

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can take place, and a disturbance in the form of a water, air, or light wave starting from one point can be made to divide itself along two paths of slightly different lengths so that the combined action of the re-united parts is to destroy all effects at the point of re-union. This interference can be also produced with the dielectric disturbance produced by an electric spark taking place between two conductors, and it can be shown that the oscillating spark produces at any point in space around it an oscillation of electric force or displacement, alternating with an oscillating magnetic flux.

The periodic effect successively produced at different points in space is such that at places equi-distant by a certain length the same electric and magnetic states or changes are being repeated at the same time, and this process is called the propagation of an electric wave.

In ending, let me then summarize very briefly the conclusions to which we have been led by experimental research during the last hundred years, as a partial reply to the question : "What is an Electric Current?"

We have seen that in association with Volta's pile and its circuit-closing wire we have energy in two forms, stored up in the circumjacent space: one evidently of a kinetic character, which we call the magnetic energy, and one which is more analogous to energy of configuration or strain, which we call electric energy. These forms of energy manifest themselves as magnetic flux round, and electric displacement between, the conductors connected to the terminals of the pile. Moreover, we find that in the case of open circuits and very rapidly alternating currents the energy associated with the conductor can be conveyed completely away from the conductor into surrounding space by a wave motion then existing as radiant energy.

The trend of physical investigation during the last half-century has been to lead us to regard energy as something distinct from matter, and yet as always associated with it.

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The conservation or indestructibility of energy induces us to think of it as an entity or physically measurable quantity having an independent claim to recognition along with that which we denominate usually material substance. We have, however, no means of recognising energy in itself, except in so far as it makes its appearance in association with matter as its vehicle, and we have no way of identifying throughout its transformations portions of that which we call energy in the same way that portions of matter can be identified in and through all their changes. We are also apparently always under the mental necessity of assuming some vehicle for energy, when it is transferred from place to place through space. We know that vast quantities of energy leave the sun, and that some of it arrives on the earth about eight minutes after its departure from the sun. The question necessarily arises, Where is it during those eight minutes? In the same manner Hertz proved that electrical energy can leave a rod in which a very rapid oscillatory current is set up and travel with the speed of light outwards in all directions. We ask, Where is it after it has left the radiator, and before it has arrived at the receiver? The answer to both these questions is that it exists as free radiant or wave energy in the æther. Both optical and electrical phenomena have compelled the assumption of an imponderable material which can be the vehicle for energy in certain forms. This medium exists in the most perfect vacuum we can produce and cannot be excluded or removed from any place.

Hence a second part of the answer to our question, What is an electric current? is that it is due to certain events or effects happening in the space-filling æther, the localisation of these events being determined by what we call the conductor.

Finally, we are met by a more searching question, viz., What are those events, and what is the nature of the effects? In order that an answer to such a question may be intelligible it must be expressed in terms of some quantities with which we are already familiar, and it must

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not involve any more assumptions than are absolutely necessary. Very briefly, then, we may say that the tendency of modern research is to seek to reduce every phenomenon in physics to pure dynamics. Whether this is a legitimate aim or a full solution of the problem of interpreting physical nature, as presented to us by our senses, I will not venture to discuss. Suffice it to say that some of the most p ofound thinkers have concluded that it is the only solution which to our present mental faculties is satisfactory.

The cardinal idea which lies at the root of all modern attempts to apprehend the machinery of inanimate nature appears to be the conviction that the facts of physics, whether we deal with visible or invisible processes, are capable of being reduced to simple mechanics. Thus Clerk Maxwell says: "When a physical phenomenon can be completely described as a change in the configuration or motion of a material system, the dynamical explanation of the phenomenon is said to be complete."

Long before Maxwell, however, Huyghens, the great contemporary of Newton, said: "All natural effects must be conceived mechanically unless we are to renounce our hopes of understanding anything in physics."

Sir John Herschel (in his Essay on the "Origin of Force") also says: "Whenever in the material world what we call a phenomenon or event takes place we either find it resolvable ultimately into some change of place or movement in material substance, or we endeavour to trace it up to some such change; and only when successful in this endeavour we consider we have arrived at its theory."

Hence, at the root of every attempt to understand physical operations seems to lie a belief that all energy is essentially mechanical energy and that it is, therefore, all either motional or configurational, or, perhaps, all motional.

The possibility of comprehending the ultimate mechanism of an electric current depends, therefore, upon our ability to ascertain the exact nature of the motional energy which consitutes a magnetic flux.

We are compelled to postulate, in the first place, an *electromagnetic medium* as the vehicle for this form of motional energy; for the simple reason that we are unable to conceive of energy *per se*, and as dissociated from some form of permanent substratum or substance acting as its vehicle. Metaphysicians must decide whether this assumption is a necessary one. The three factors—matter, æther and energy, are at present unresolved equations, or algebraical expressions, in terms of which physical phenomena are interpreted. If atomic matter should eventually be shown to be a particular association of configurational or motional energy with æther, in accordance with the vortex theory of Lord Kelvin, or the æther electronic theory of Dr. Larmor, it will merely mean that the tri-unity is resolved into a duality, and that one of the factors can be expressed in terms of the other two. In order that we may explain wave propagation in the æther we are compelled to postulate for it at least two qualities; one analogous to, or actually the same as, inertia in sense-perceived

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matter, and the other an elasticity quality or a self-recovering deformability of some kind. There are arguments which show that this elasticity cannot be of the compressional kind with which we are so familar in gases; and also some strong objections to assuming it to be an elasticity of form or resistance to shearing as in the case of ordinary solids. Lord Kelvin has evolved the original idea of a *rotational æther;* a medium having no compressibility and no resistance to shearing, but each elementary portion of which resists absolute rotation in any direction. This conception enables us to deduce mathematically consequences which are in accord with experience, and evades the difficulties inseparably associated with the elastic solid or jelly theory of the æther.

Hence any detailed answer to our question can only be expressed in terms of some dynamical theory as to the constitution of the æther and its relations to sense-perceived matter. To touch even the outlines of the æther theories already constructed, examined or abandoned would be to tax your indulgence and my powers more seriously than I can venture now to do. When this century opened Dr. Thomas Young made the first really competent attempt to apply the theory of a universal æther, assumed to be possessed of merely mechanical properties, to the explanation of the phenomena of light. Twenty years afterwards Ampère threw out a suggestion that the same hypothesis might supply the means of interpreting electrical facts. Joseph Henry upheld a similar view. Faraday strongly supported it. Clerk Maxwell, in his splendid dynamical theory of the electromagnetic field, published in 1864, first gave definite mathematical form and expression to a theory including, not only electric and magnetic, but also optical, phenomena in its grasp. Hertz in 1887, with magnificent insight, verified its fundamental assumptions.

Ampère, 1822 (*Mèmoires de l'Institute* of France for 1823, pp. 294–299), says he "endeavoured to account for the force which is exerted between two elements of conducting wires conveying a current by the action of the fluid which is distributed in space and whose vibrations produce the phenomena of light."

Faraday, 1851 ("Experimental Researches in Electricity," § 3,075, Vol. III.), says: "For my own part, considering the relation of a vacuum to the magnetic force and the general character of magnetic phenomena external to the magnet, I am more inclined to the notion that in the transmission of the force there is an action external to the magnet, than that the effects are merely due to attraction and repulsion at a distance. Such an action may be a function of the æther, for it is not unlikely that, if there be an æther at all, it should have other functions than simply the conveyance of radiations."

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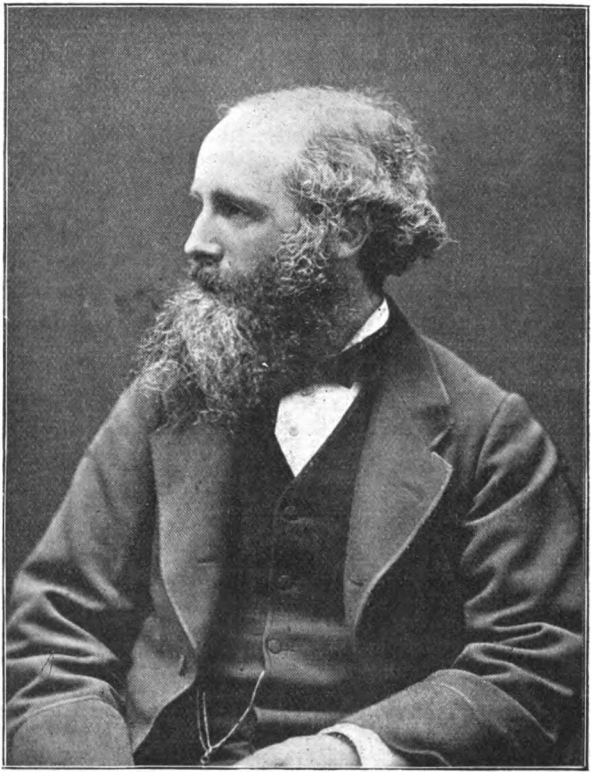
One of James Clerk Maxwell's pre-eminent claims to fame rests upon his achievement in having raised these vague suggestions to the dignity of a scientific theory capable of definite proof. The illustrious French mathematician, Joseph Louis Lagrange, published in 1788 his "Mécanique Analytique," and in this "scientific poem," as Sir William Rowan Hamilton called it, he expounded the principles of a dynamical analysis in the form of certain equations, called Lagrange's equations. The aim of Lagrange was to bring dynamics under the power of the calculus. These equations express in the most general manner



JAMES CLERK MAXWELL,

Sometime Cavendish Professor of Experimental Physics in the University of Cambridge.

the relation of the kinetic or motional energy of a system of bodies and the forces, velocities and displacement experienced by each of them. Recognising that systems possessing electric and magnetic energy could be equally considered as coming within the dominion of these equations, Clerk Maxwell, with profound insight, applied the Lagrangian equations to express the relations

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between the electromagnetic energy, the electromotive forces, the electric currents and displacements in any system exhibiting electric or magnetic energy. In this manner he constructed a certain system of mathematical equations which state the relations of the fundamental electric and magnetic quantities in terms of the specific constants of the medium or materials in which the operations are taking place. Finally, by one mode of interpretation of the mathematical symbols, he identified Faraday's specific inductive capacity as the constant whose reciprocal expresses the electric elasticity of the medium, and Lord Kelvin's magnetic permeability as that which defines its density, and showed that the reciprocal of the square root of their product was a number expressing the velocity with which an electric wave or progressional electric displacement would be propagated through the medium. It followed at once from this result that, for all practically non-magnetic media, the square root of the specific inductive capacity or dielectric constant should be numerically equal to the optical refractive index of the substance.

Moreover, Maxwell showed that the velocity of propagation of an electric displacement through a medium could be measured indirectly by obtaining the ratio of certain purely electrical measurements of electric quantity, capacity, or resistance made by two different methods. In the last twenty years an enormous number of observations have been made to determine this electromagnetic velocity (always denoted by "v") and it has invariably been found to be identical with the best observed values of the velocity of light. Also it has been found (by Fleming and Dewar) that, in the case of dielectric media, if the specific inductive capacity is measured at a sufficiently low temperature, or (by others) with an alternating electromotive force of very high frequency, the square root of its value is practically identical for a large number of substances with the refractive index for very long waves as deduced from optical experiments.

Lastly, methods of producing and detecting electric waves have been invented, which make it possible to imitate all known optical phenomena, such as reflection, refraction, double refraction, dispersion, polarisation, rotation of plane of polarisation and other effects by means of invisible electric waves produced by an oscillatory electric spark and detected by a suitable sensitive tube or receiver.

Thus has been constructed a body of almost irrefutable argument that the notion which was, at the hands of Ampère, only a brilliant suggestion, with Faraday and Henry a cherished conviction, built up by Maxwell into a scientific theory, experimentally confirmed by Hertz and all his illustrious followers, is, indeed, something in advance of a mere physical hypothesis, and is probably the greatest insight into the hidden mechanism of nature which has yet been made by the intellect of man.

The closing years of this century have seen the accumulation and arrangement of knowledge, gathered by investigators in many lands, affording well-nigh irresistible proof that electric and magnetic effects, although manifesting themselves in connection with material substances, have their seat in actions taking place in an intangible

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medium, the ripples in which are rays of light, and billows the æther waves we are learning to employ.

This medium is capable of sustaining certain distortions or changes of internal configuration which are probably the source of electric effects, and also certain motions which are the possible basis of magnetic phenomena. It is also able to propagate a wave-motion, and the particular eye-affecting radiation we call light is only one little octave of a boundless gamut of æther waves, some twenty-one octaves of which are familiar to us at present.

If one-thousandth of a millimetre is called as usual *one micron*, and denoted by 1μ, we can make a table of æther waves known wave length as follows :—

The shortest measured waves of ultra-violet light have a wave length of $0{\cdot}1\mu$, as determined by Schumann in 1893. The following is, then, the range of known wave length of ultra-violet, visible and ultra-red radiation.

$0{\cdot}1\mu$ } Two octaves of ultra-violet radiation.
$0{\cdot}2$ } Shortest measured wave length $= 0{\cdot}1\mu$.
$0{\cdot}4$ } One octave of visible radiation $0{\cdot}43\mu$ to $0{\cdot}75\mu$.
$0{\cdot}8$ }
$1{\cdot}6$ }
$3{\cdot}2$ }
$6{\cdot}4$ } Six or seven octaves of ultra-red radiation or dark heat. Wave length of radiation from Leslie cube, as measured by Langley $= 13\mu$.
$12{\cdot}8$ }
$25{\cdot}6$ } Wave length of longest dark heat rays measured by Nicols in 1898 $= 67\mu$.
$51{\cdot}2$ }
$102{\cdot}4$ }

Much attention has been given lately to the production of heat rays of very great wave length. By repeated reflections of the radiation from a Welsbach gas burner from the surface of rock salt or sylvine plates Messrs. Rubens and Aschkinass have sifted out heat rays having a wave length of $61{\cdot}1\mu$. These waves are 70 times shorter than the shortest electric waves yet obtained. They are strongly absorbed by fluorspar, glass and calspar, also by alcohol and ether. But bisulphide of carbon, benzol and petroleum transmit them freely. Olive oil transmits the rays reflected from sylvine, but absorbs those from rock salt.

It is a suggestive fact, that the bodies which do not absorb these heat rays of great wave lengths belong to that class for which at ordinary temperatures the dielectric constant is equal to the square of the refractive index for infinitely long waves. Such bodies have no absorption band in the infra red spectrum.

Following on this, we have six octaves of unknown radiation lying between the wave lengths, 67μ and $4{,}000\mu$. Then we enter the region of Hertz waves, of which at least twelve octaves and perhaps much more is known. The shortest Hertz waves yet produced by Lampa have a wave length of $4{,}000\mu$ or four millimetres, and others not infrequently used have a wave length, lying 12 octaves above, viz., 13 metres. Hence, with the exception of the six octaves of unknown radiation, we may say that we are perfectly familiar with

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two octaves of ultra-violet radiation, one octave of luminous, six octaves of ultra-red, and 12 or more octaves of Hertz wave. There is, however, nothing to mark an upper or lower limit.

Electrical oscillations set up in the sun or stars may excite æther waves millions of miles in wave length, and we cannot say what effects may not be produced by æther waves lying far beyond the gamut of our experience.

Hence we see that, starting from Volta's discoveries a century ago, the conclusion has been reached that the actions we call an electric current, if alternated rapidly enough in direction, would end by producing a ray of light. We are, however, as yet in the region of conjecture when we attempt to formulate a specification of the exact nature of the motional and configurational changes which must be at the root of observed effects. To devise a theory of the æther such that from the simplest possible assumptions can be deduced the facts of electricity, magnetism and optics may be said to be the aim of physical inquiry at the present time.

Whilst, under the guidance of its gifted leaders the scientific army marches on, it continues to dispense material benefits which are appreciated by all mankind. But it also, as we at least shall freely admit, fulfils another and perhaps more perfect service. It reveals to our eyes the amazing complexity of structure which underlies the simplest of surrounding things, and points out regions yet more wonderful waiting to be explored. The unravelling of the tangled skein of cause and effect in the outward world of Nature affords to many intellects a fascinating pleasure; and it cannot be denied that, when pursued in a disinterested and reverent spirit, it is one of the highest occupations of the human mind.

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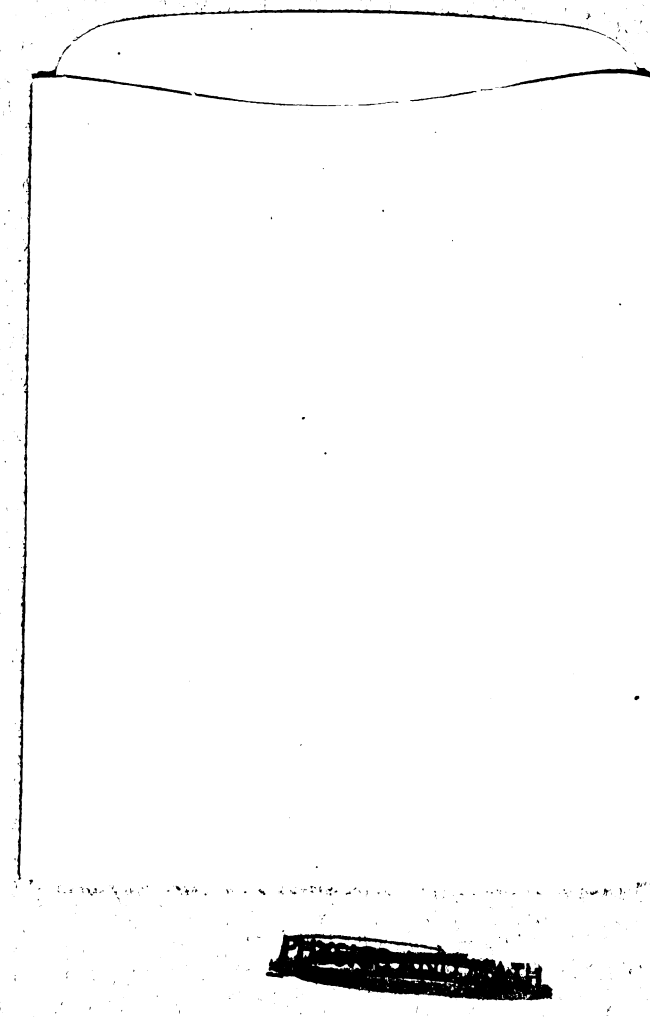

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